DOCUMENT RESUME

ED 183 373 SE 029 958

TITLE	Fundamentals of Electric Circuits. Laboratory Manual.
INSTITUTION	Wentworth Inst., Boston, Mass.
SPONS AGENCY	National Science Foundation, Washington, D.C.
PUB DATE	67
NOTE	152p.
EDRS PRICE	MF01/PC07 Plus Postage.
DESCRIPTORS	*College Science: Curriculum Guides: Electric Circuits: *Electricity: Electronics: Higher Education: *Laboratory Manuals: *Physics: Science Activities: Science Courses: *Science Experiments: Science Laboratories: Teaching Guides

ABSTRACT

This laboratory manual consists of three major sections. The first section deals with Direct Current (DC) fundamentals, and is divided into 17 phases leading towards the design and analysis of a DC ammeter and a DC voltmeter. Each phase consists of facts and problems to be learned in the phase, preliminary discussion, laboratory operation procedure, preparation test, and concluding discussion. The second section is designed to familiarize the student with the oscilloscope. The third section deals with Resistive-Capacitive (RC) transients. The purpose of this section is to introduce some of the basic principles of RC networks and Resistance-Inductive (RI) networks. Directions for the use of students' laboratory kits are also included. (HM)

****
* Reproductions supplied by EDRS are the best that can be made *
* from the original document. *
****

ED183373

U.S. DEPARTMENT OF HEALTH,
EDUCATION & WELFARE
NATIONAL INSTITUTE OF
EDUCATION

THIS DOCUMENT HAS BEEN REPRODUCED EXACTLY AS RECEIVED FROM THE PERSON OR ORGANIZATION ORIGINATING IT. POINTS OF VIEW OR OPINIONS STATED DO NOT NECESSARILY REPRESENT OFFICIAL NATIONAL INSTITUTE OF EDUCATION POSITION OR POLICY

"PERMISSION TO REPRODUCE THIS
MATERIAL HAS BEEN GRANTED BY
Mary L. Charles
NSF

TO THE EDUCATIONAL RESOURCES
INFORMATION CENTER (ERIC)."

Fundamentals of Electric Circuits

Laboratory Manual

Prepared Under a Grant From

The National Science Foundation

Copyright © 1967 by

Wentworth Institute

Department of Electronic Engineering Technology

Boston, Mass.

SE 029 958

FUNDAMENTALS OF ELECTRIC CIRCUITS

LABORATORY MANUAL

TABLE OF CONTENTS

page
Vector Kit directions.. 1

Principal Problem One: D.C. Fundamentals.......................... 3

Phase 1: Resistor Color Code................................ 6

Phase 2: Laboratory Wiring Techniques......................... 9

3: Voltage Relationship of Linear Components............ 12

4: Current-Voltage Relationship of a Nonlinear Device.... 19

5: Series Circuits.................................. 29

6: Parallel Circuits................................. 37

7: Power... 44

8: Maximum Power Transfer........................... 52

9: Loop and Nodal Analysis.......................... 60

10: Thevenin's Theorem............................... 70

11: Norton's Theorem................................. 77

12: Superposition Theorem............................ 84

13: Voltage Dividers................................. 91

14: Current Dividers................................. 97

15: Ammeters.. 103

16: Voltmeters...................................... 112

17: Loading Effect of Voltmeters..................... 118

Principal Problem Two: Oscilloscope.......................... 124

Principal Problem Three: RC Transients....................... 136

VECTOR KITS

The vector breadboarding kits (one for each pair of students) are to be signed out for the semester. Their return in good condition, and complete, will be the responsibility of the student. Students will be charged for damages and/or losses. Each kit will be stored in the Electronics Department Stockroom when not in use in the laboratory.

Each kit contains:

4 aluminum side rails and fasteners
1 aluminum bottom plate and screws
1 piece of phenolic vectorboard, punched
2 bus bars
20 spring clip terminals

Check your kit when you recieve it. Sign receipt indicating material above has been received in good condition.

Directions for use:

(1) Remove the two screws at one end of the bottom plate. Gently pull on the short aluminum side rail and remove it. Small parts are stored inside.

(2) Special cables are provided for connecting to Wentworth Institute standard laboratory instruments. These have a banana plug on one end, and clips that fit between the coils of the spring on the spring clips.

(3) For short connections between spring clips, use bus wire, obtainable from the stockroom. For longer connections, use spaghetti on the bus wire, or hookup wire.

(4) When the kit is to be stored, reverse the phenolic board so that the parts are inside the case. Put loose parts inside the case and replace the end rail. Replace the two screws on the bottom plate and turn the kit into the stockroom for storage.

(5) Separate from the vector kit, each student will receive 71 resistors which will be turned in at the end of the semester.

Principal Problem

Number 1

D.C. Fundamentals

Statement of the Problem:

This principle problem is divided into 17 phases leading towards the successful design and analysis of a d-c ammeter and a d-c voltmeter. In order to complete the solution we must gain experience with basic circuit analysis.

Preliminary Discussion:

The d-c voltmeter and ammeter are the most important and basic instruments. Their use must be mastered by the technician. We will of necessity, apply Ohm's law, loop and nodal analysis, and network theorems to complete the problem. Each step of the problem will be based on the successful completion of the preceeding step. Much of the required guidance will be furnished in this manual at the place where it will be needed. This problem in turn will be the foundation for the next, and so on, for the rest of the entire curriculum. You will need to master new measuring techniques as they are required, and apply what you can learn, both in the classroom and the laboratory, to this problem. The instructor will point out other related concepts and similar problems which you can solve after increasing your experience to the level required by the solution of this problem. Please write all your data, calculations, conclusions reasoning and observations immediately in the notebook. Retain a record of all your errors since we sometimes learn more by our errors than our successes.

Facts and Principles to be learned in this problem.

The facts and principles to be learned in the princiapl problem will be enumerated or contained in the preliminary discussion of each phase.

Phase I Resistor Color Code

Facts and principles to be learned in this problem

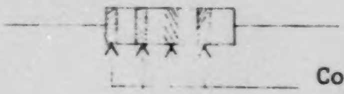
(1) Memorize the resistor color code

(2) Learn how to use the G.R. Bridge

(3) Characteristics of resistors are classified by color code

Preliminary Discussion:

Resistors are classified according to their resistive value in ohms, resistance tolerance, and to their power rating in watts. Figure 1 illustrates a physical diagram and the electrical symbol for a resistor -



Physical diagram

Electrical symbol

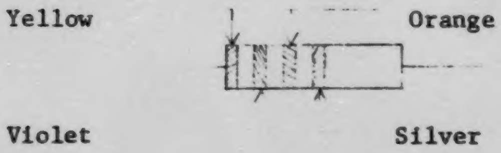
Note that the resistor has four colored bands around the resistor which indicates the resistance value and the tolerance. The first band represents the first significant figure. The second color represents the second significant figure. The third color represents the multiplying factor. The fourth color (gold or silver) represents the tolerance. The standard resistor color code is listed in Table I:

Table I - Resistor Color Code

Color	Significant Figure	Multiplying Value
Black	0	1
Brown	1	10^1
Red	2	10^2
Orange	3	10^3
Yellow	4	10^4
Green	5	10^5
Blue	6	10^6
Violet	7	10^7
Gray	8	10^8
White	9	10^9
Gold	± 5% tolerance	
Silver	±10% tolerance	
No Color	±20% tolerance	

Table 1 - Resistor Color Code

As an example, let us determine the resistive value and tolerance of the resistor shown below



The first and second bands are yellow and violet respectively. The multiplying band is colored orange and the tolerance band is colored silver. Referring to Table I yields a resistance of:

$47 \text{ X } 10^3 = 47{,}000$ ohms

Laboratory Operation Procedure:

1. From color code determine the resistive value of the 71 resistors you have received. Make a list in your notebook for this will be very useful in later work.
2. Obtain and study the type 1650A Impedance Bridge with the Condensed Operating Instructions. Measure the resistance of ten different resistors on the 1650A Impedance Bridge and compare with the color values. Do these values lie within the tolerance indicated.
3. Measure the same ten resistors with an ohmmeter and compare results.

Preparation Test:

Determine the resistive value and tolerance of the following resistors:

First Band	Second Band	Third Band	Fourth Band
Brown	Green	Red	Gold
Black	Orange	Green	Silver
Violet	Red	Violet	No Color

Concluding Discussion:

Now that the use of the color code has been mastered, it will be applied in some of the following phases.

Phase 2 Laboratory Wiring Techniques

Facts and Principles to be learned in this phase.

1. To learn how to construct a circuit from a schematic diagram.

Preliminary Discussion: Before any electronic problems can be solved a basic knowledge plus a minimum level of experience must be attained. Only after this foundation has been completed, can the student divert his attention from how to use the tools of electronics to applying these tools. This phase is designed so that the student can gain an elementary proficiency in constructing a circuit from a schematic diagram and gain experience in the connection of meters.

Laboratory Operation Procedure:

Connect each of the circuits shown in the schematic diagrams below. An instructor must check each set up before you proceed with the next one.

Note: Do not apply power to any of these circuits.

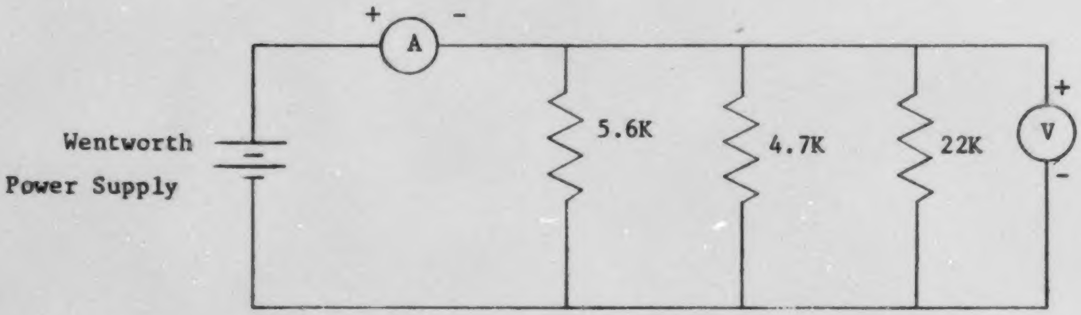


Figure A

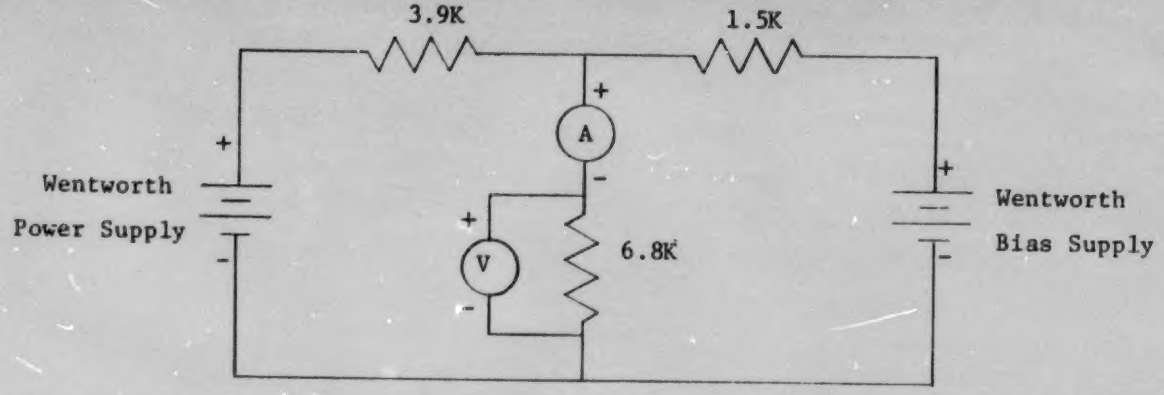

3.9K
1.5K
A
+
-
Wentworth
Power Supply
+
-
V
6.8K
Wentworth
Bias Supply

Figure B

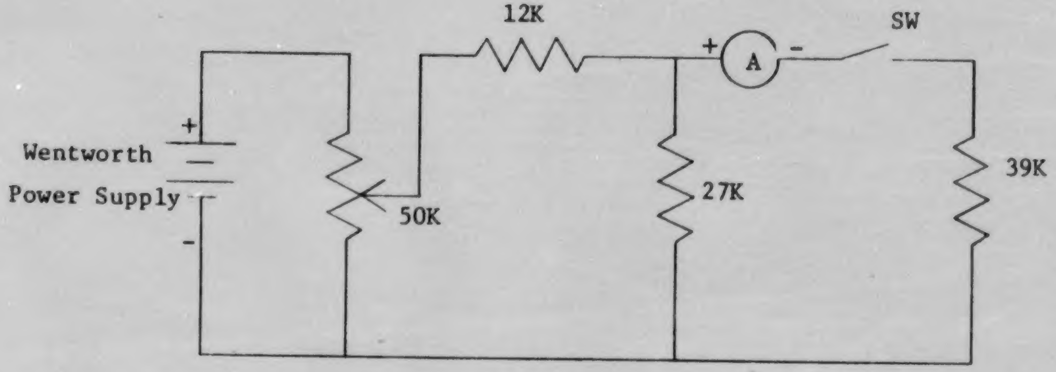

12K
SW
A
+
-
Wentworth
Power Supply
50K
27K
39K

Figure C

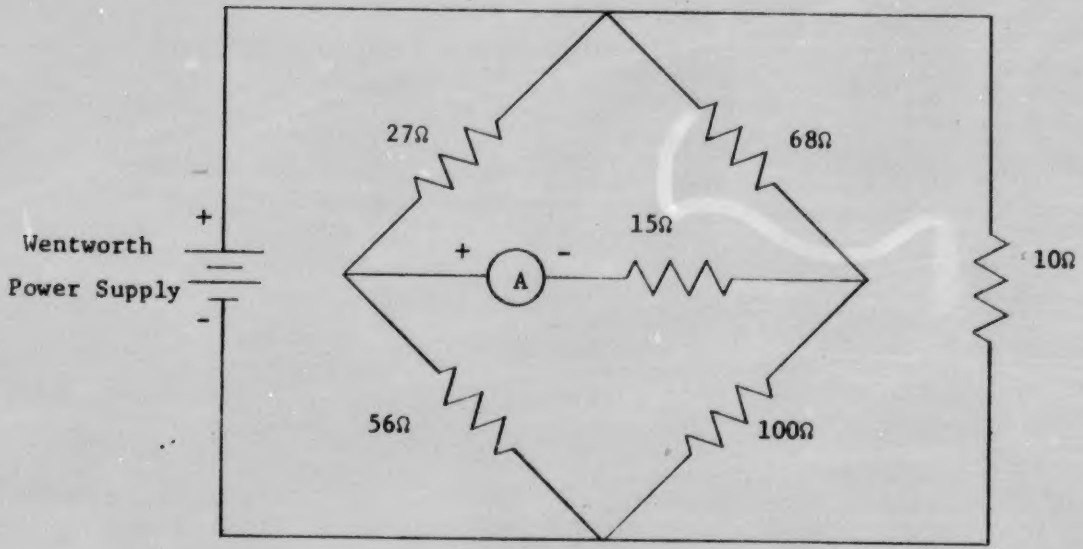

27Ω
68Ω
15Ω
A
+
-
Wentworth
Power Supply
10Ω
56Ω
100Ω

Figure D

13

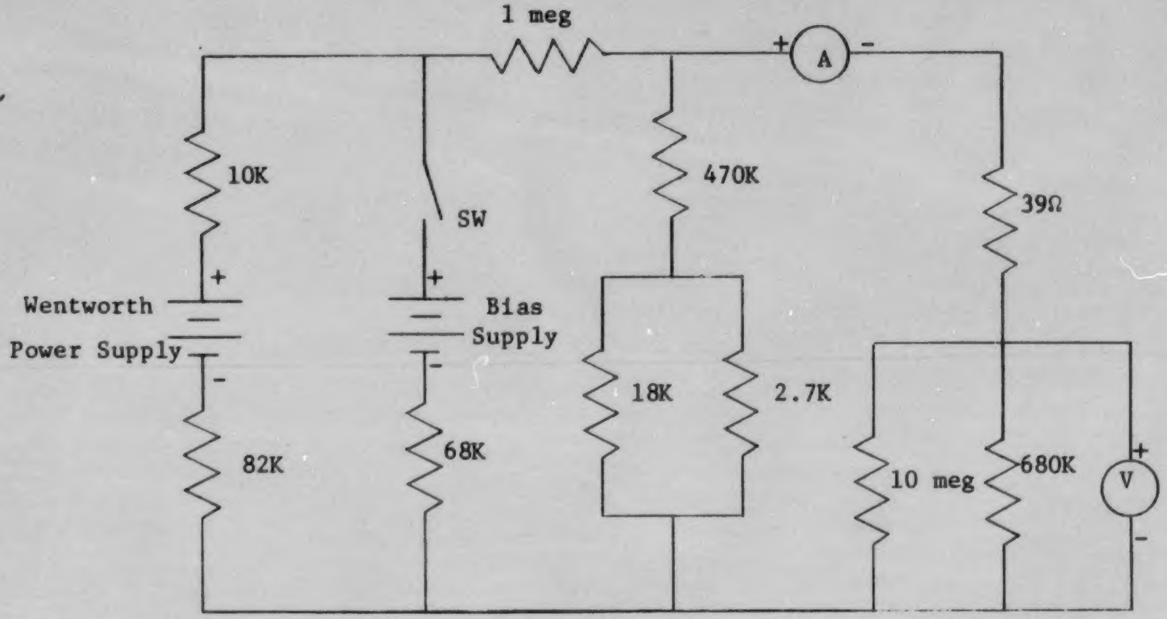

1 meg
+
A
-
10K
SW
470K
39Ω
+
Wentworth
Power Supply
-
+
Bias
Supply
-
18K
2.7K
82K
68K
10 meg
680K
+
V
-

Figure E

__Concluding Discussion__: It should be concluded now that the most practical way to construct a circuit is to lay it out as closely as possible to the circuit schematic. When this is done, it is easier to troubleshoot and identify different components.

14

Phase 3 Voltage Relationship of Linear Components

Facts and Principles to be learned in this phase:

1. Ohm's law
2. Characteristics of a series circuit
3. Characteristics of a parallel circuit.

Preliminary Discussion: Ohm's law states that the value of the current in a linear resistor is directly proportional to the applied emf and inversely proportional to the resistance. Mathematically this is expressed as:

$$I = \frac{E}{R}$$

where I is the current in amperes, E is the applied emf in volts and R is the resistance in ohms.

This phase is concerned with the current - voltage relationship of a linear resistor. If we assume that the resistance is constant, a plot of equation (1) results in a straight line which passes through the origin and has a slope of $\frac{1}{R}$ on these coordinates. This is illustrated in Figure 1:

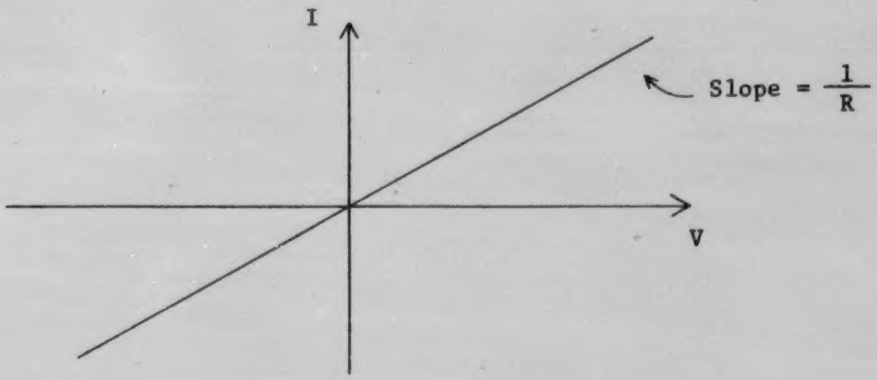


Figure 1 - Plot of Equation 1.

This curve is known as the volt-ampere characteristic of the resistor. Since curve is a straight line, the resistor is a linear device. Note that for negative values of applied emf, the current reverses but the characteristic curve is still linear. A nonlinear device, as one might suspect has a current-voltage-characteristic that is not a straight line. A non-linear device will be discussed in phase 4. Most active devices such as transistors and vacuum tubes are non-linear but they do have regions where their current-voltage characterisitics are linear.

Laboratory Operation Procedure:

1. Set up the circuit in Figure 2.

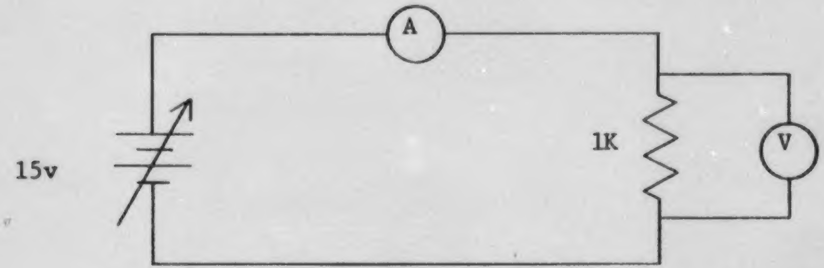


Figure 2 - Circuit to determine the current-voltage relationship of a resistor

2. Vary the supply voltage from -15 volts to +15 volts in 3 volt steps and record the current and voltage readings of the 1K ohm resistor.
3. Plot the current versus voltage.
4. Determine the resistance from the slope of the curve.
5. Measure the value of the resistor on the G.R. bridge and compare with your answer in step 4.

6. Repeat for R = 3.3 K ohm and again for R = 10 K ohm, plotting the current-voltage characteristic of each resistor on the same graph as step 3 and compare the slopes of the three curves.

7. Although the following method is not the best way to handle linear circuits, it is very helpful in analyzing non-linear circuits. This method will be utilized in the next phase of this problem. The following is a graphical approach in analyzing a network. Let us consider the simple series circuit shown below.

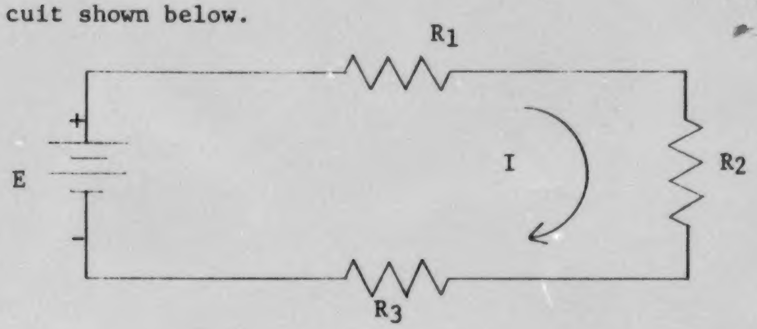


Figure 3 - Simple Series Circuit

It is desired to determine the current flowing in this circuit. Once again the analytical method is the easiest way to solve for the current, but we will solve for this circuit by graphical methods. We can obtain the IV curve for the three resistances in series by the following method. Since the resistors are connected in series the current will be the same in each resistor. Now from the curves of step 6 we take and add voltages of the three IV curves for given values of currents. This should be repeated for three more currents. Connecting these points results in a straight line. This is the composite IV curve for the three resistors in series.

This procedure is illustrated in Figure 4.

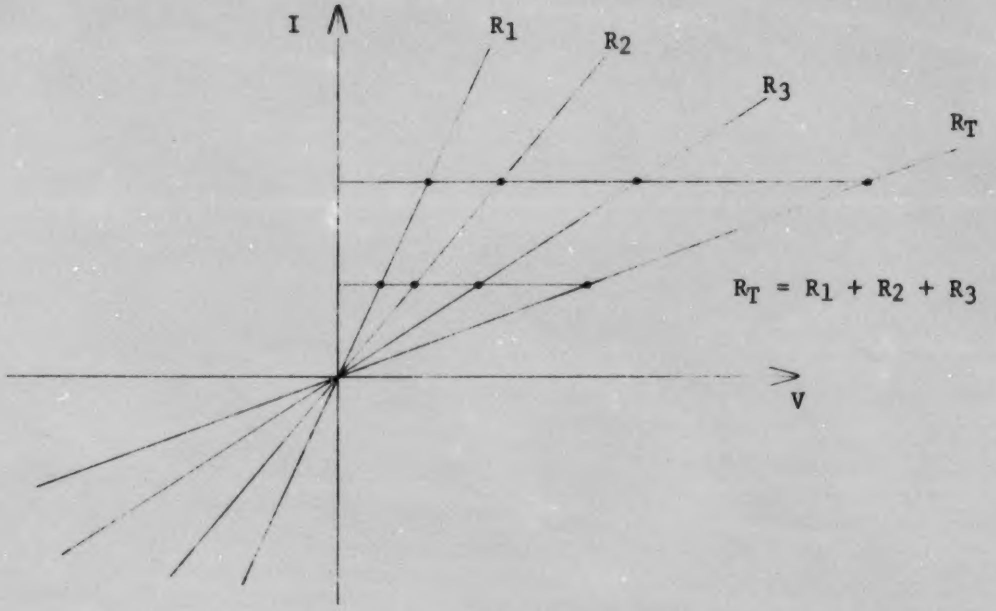


Figure 4 - Graphical method of determining composite IV curve for three resistors in series.

Once this composite IV curve is obtained we can determine what current will flow for a given source E.

8. Using the three resistors of steps 2 and 6, and a supply voltage of 10 volts, connect them as shown in Figure 3. Measure the current which flows. From your composite IV curve of the three resistors in series, determine the current which should flow. Compare these two currents.
9. Repeat step 7 for the case where the three resistors are in parallel. Note that in this case, the voltage across each resistor is the same, therefore we will have to add currents for given values of voltages in order to obtain the composite IV curve.

Preparation Test:

1. What is the resistance of a piece of #18 gauge wire fifty feet long which allows 250 amperes to flow when connected to a 100 volt source?

2. What current will flow through a 39 kilohm resistor when connected to a 117 volt source?

3. Which of the following coordinates do not fall on the volt-ampere characteristic of a 1500 Ω resistor?

   a) 225 volts @ 150 ma   b) 150 volts @ 100 ma

   c) 15 volts @ 1.5 ma   d) 200 volts @ 133 ma

4. With the resistance held constant, as the voltage increases, the current _______________.

5. As the resistance increases, the slope of the volt-ampere curve _____________________.

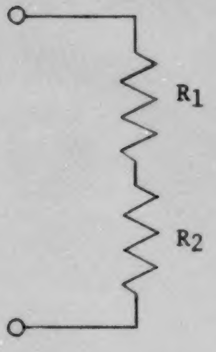
6. Four out of five resistors connected in series are as follows: 100 ohm, 680 ohm, 470 ohm, and 1000 ohm. Find the remaining resistor if the total voltage across all five resistors is 200 volts with 65.2 ma flowing through them.

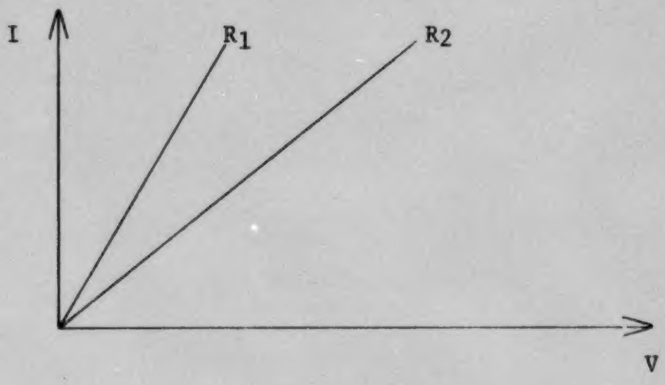
Homework Exercises:

Draw the composite curves for the following circuits.

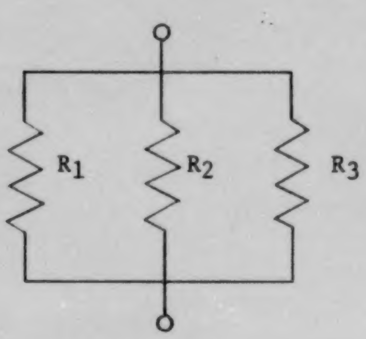
Show Work.

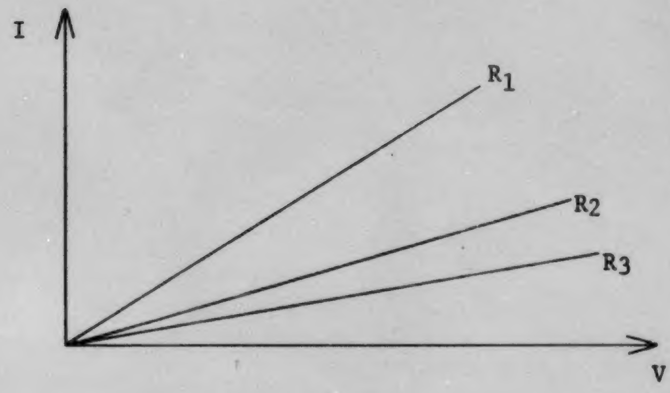
(1)



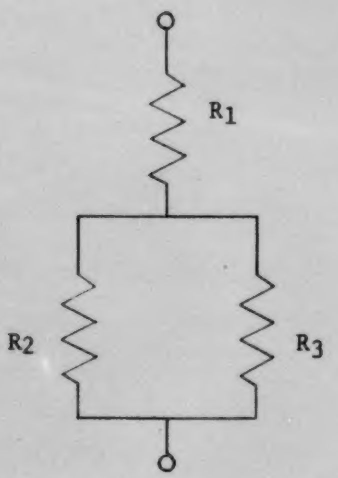


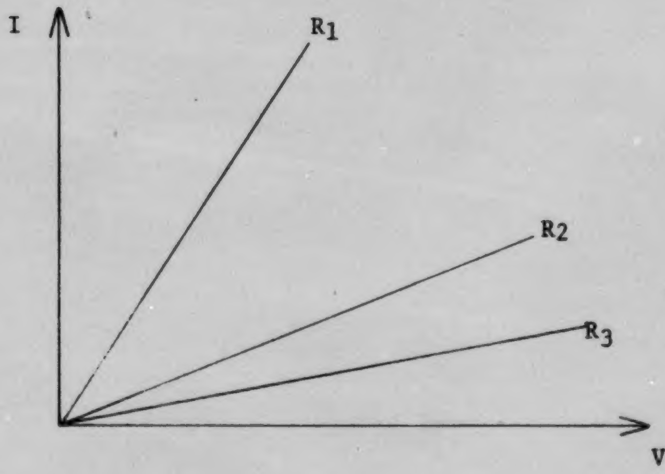
(2)





(3)





Concluding Discussion:

In this phase, we have solved a simple series and a simple parallel network using graphical techniques. In some of the following phases, we will solve more complex circuits with the use of some theorems and applying systematic treatments.

Phase 4 Current-Voltage Relationship of a Nonlinear Device

Facts and Principles to be learned in this phase:

1. To obtain IV characteristics of a nonlinear device.
2. Use of the IV characteristic curve
3. Graphical solutions of nonlinear circuits

Preliminary Discussion:

Figure 1 illustrates the IV characteristic of a nonlinear device, the PN junction diode.

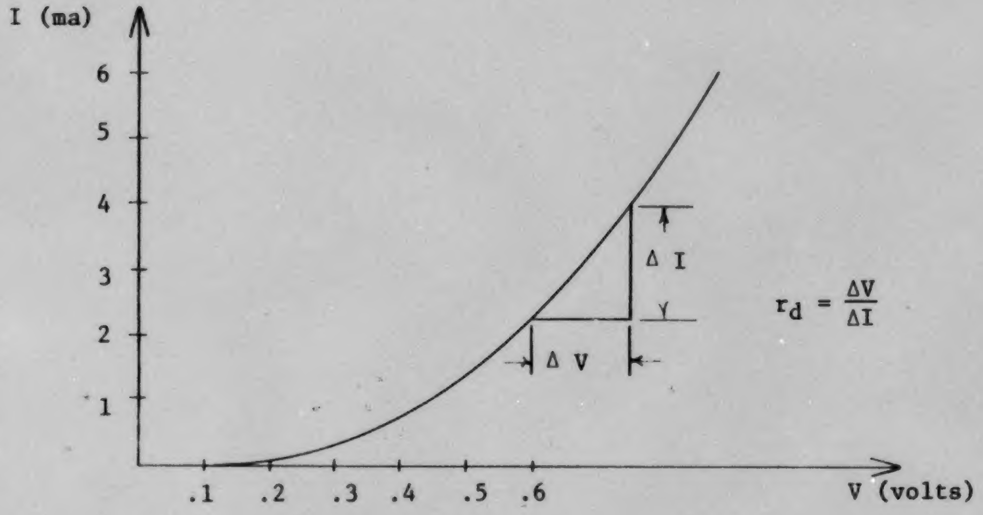


Figure 1 - IV Curve of PN junction diode.

One way of defining a very useful "resistance" is, the ratio of a small voltage change to the corresponding change in current. This useful parameter is called the incremental resistance. This is illustrated in Figure 1. Note that this resistance, (r_d), changes at different points along the curve.

Laboratory Operation Procedure:

1. Construct the circuit of Figure 2

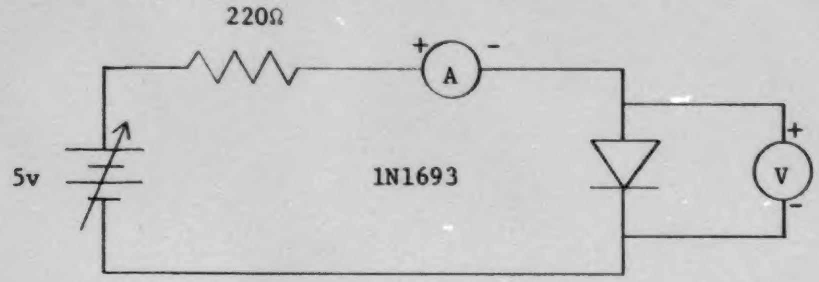


Figure 2 - Circuit used to obtain data to plot IV curve of diode

2. The resistor R is used to limit the current through the diode since excessive current may destroy the diode. Vary the power supply form 0 to +5 volts and obtain corresponding readings of diode current and diode voltage.
3. Plot diode current versus diode voltage. This results in the IV characteristic of the PN junction diode. We should note that the PN junction diode is a temperature dependent device and applying a voltage across it as in Figure 2, will heat the diode. The increase in temperature wlll change the diode's characteristics. Later we will show how to avoid this heating effect by obtaining the IV characteristic with sweep techniques.
4. As an application in the use of the diode IV curve, let us consider the circuit of Figure 3.

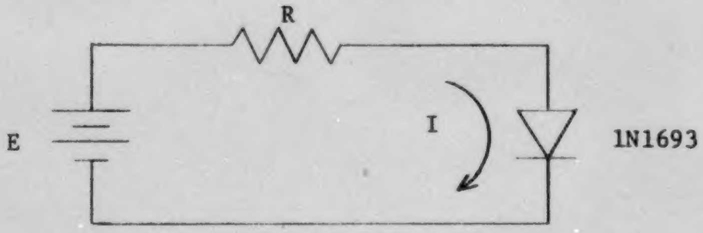


Figure 3

Since the resistance of the diode is a variable quantity it is not easy to predict by analytical methods the current I, which flows in the circuit of Figure 3. It is possible to predict the value of current by graphical methods. There are two general graphical solutions. These are:

1. Composite IV - curve
2. Load - line method

The first method is as follows:

First it is required that we have the IV characteristic of the diode. We then plot the IV characteristic of the resistor on the same plot. Since this is a series circuit and the current is common to both components, we add the voltage of the resistor to the voltage of the diode for given values of current. This results in a composite IV curve which represents the resistor in series with the diode. This is illustrated in Figure 4.

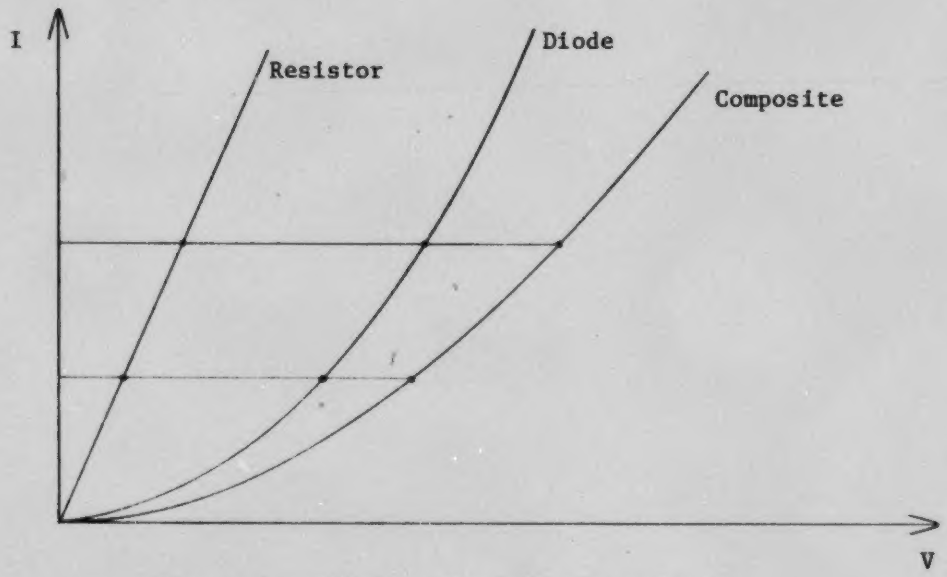


Figure 4 - Illustration of how to obtain Composite Curve of a Resistor in Series with A Diode

If the value of E is given, we can obtain the circuit current by projecting up to the composite curve and reading the current. Note that we can also pick off the voltage drop across the resistor and across the diode.

For the circuit of Figure 5, determine the composite IV curve of the resistor and diode. Use the IV curve from step 3.

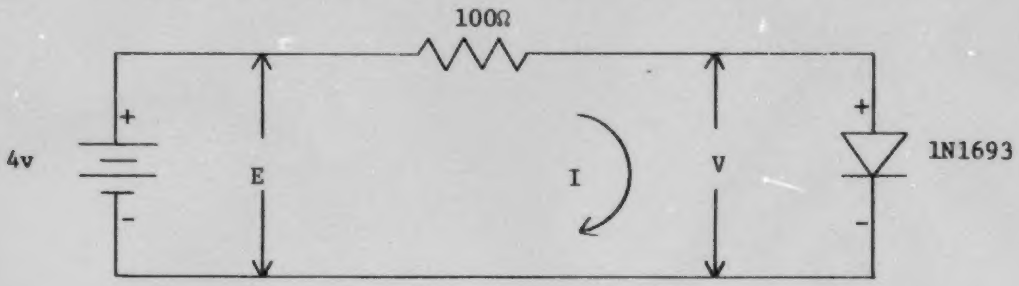


Figure 5.

For the given supply voltage, determine graphically the current which will flow. Construct the circuit of Figure 5 and measure the current, the voltage drop across the 100 ohm resistor and the voltage drop across the diode. Compare your results with the graphical approach methods.

The second graphical procedure, the load - line method, is much faster since we do not have to determine a composite IV curve. The procedure is as follows:

It is desired as before to determine the current and voltage drops of Figure 5, Writing Kirchoff's voltage equation results in,

$$V = E - IR \qquad (1)$$

where V is the drop across the diode. Solving for I in equation (1) and plotting this on a set of IV coordinates results in a straight line. Therefore only two points are required in equation (1).

One point can be determined be setting I equal to zero in equation (1). This results in V = E. Another point on the straight line is obtained by setting V to zero. This results in I = E/R

Summarizing,

$$I = 0,\ V = E$$

$$I = E/R,\ V = 0$$

Once these two points are located on the coordinates, they can be connected with a straight line.

Plotting this equation on the IV curve of the diode results in a straight line which intersects with the diode curve. The straight line is commonly referred to as the load line. The point of intersection is known as the Q point or operating point. This gives the diode current (circuit current) and the diode voltage.

Figure 6 illustrates the above procedure.

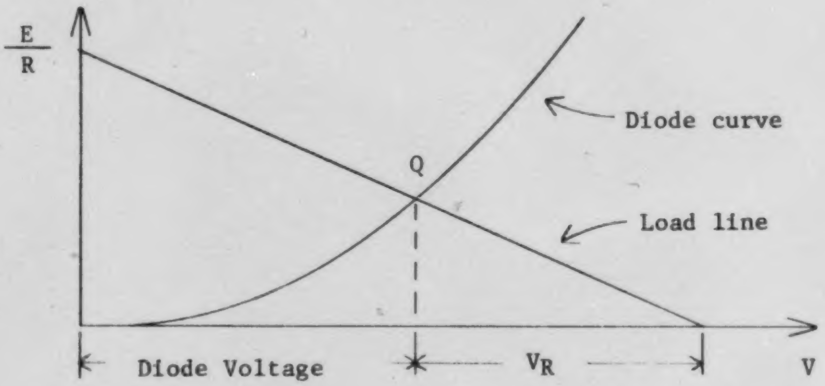


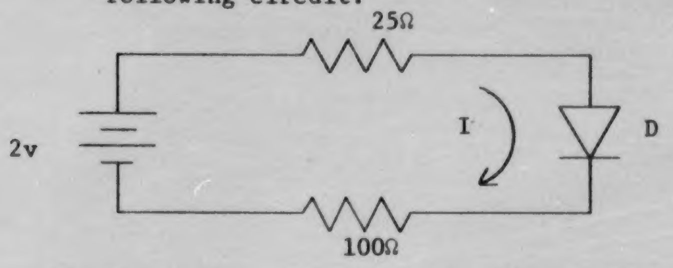
Figure 6 - Illustration of Load-line.

Construct the load line for Figure 5 on the IV curve of the diode. Determine the diode current and voltage drops and compare with the measured values.

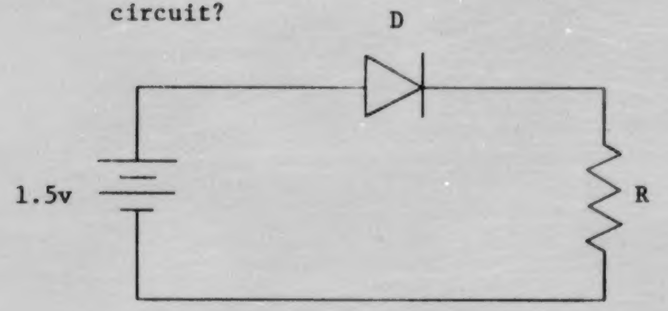
Preparation Test:

Use diode characteristic curve on page 28 to solve the following problems.

1) Find I and the voltage drops across each component in the following circuit.



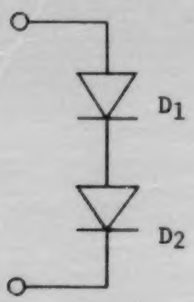
2) What value of R will allow 10 ma to flow in the following circuit?

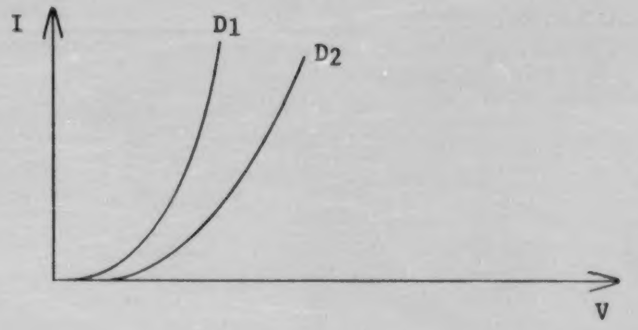


Homework Exercises:

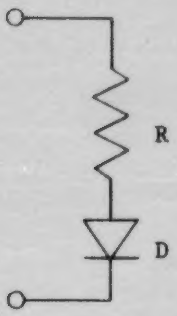
Draw the composite curves for the following circuits. Show Work

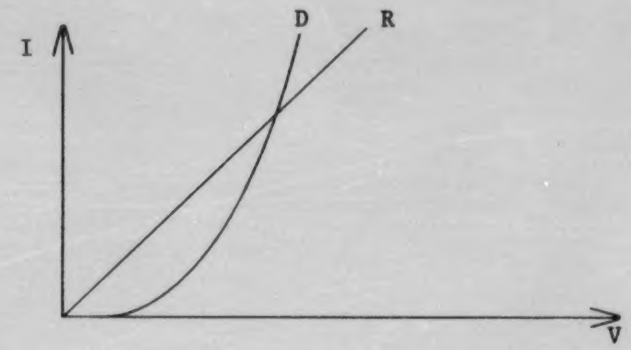
(1)





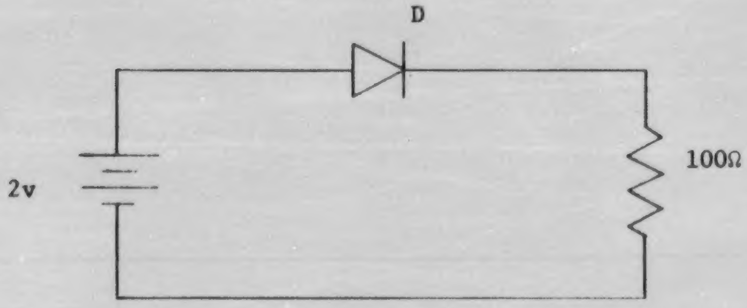
(2)





For the following problems, use the curve on page 28

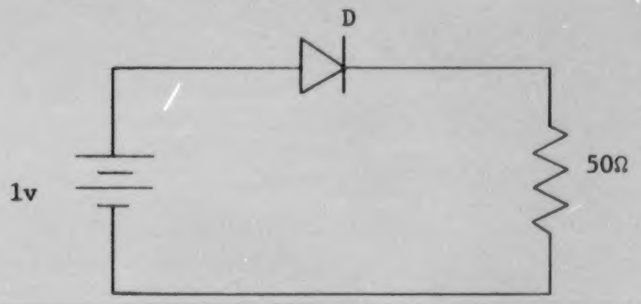
3) Calculate the total resistance of the circuit at a power supply voltage of 2 volts, after finding the composite curve.



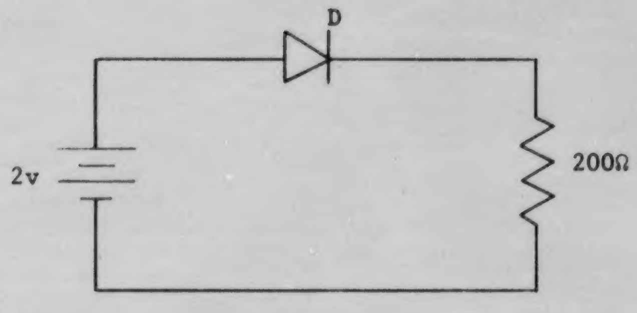
Solve the following circuits for current, voltage across the diode, and voltage across the resistor by the composite curve method and the load line method.

Compare the results:

(4)



(5)

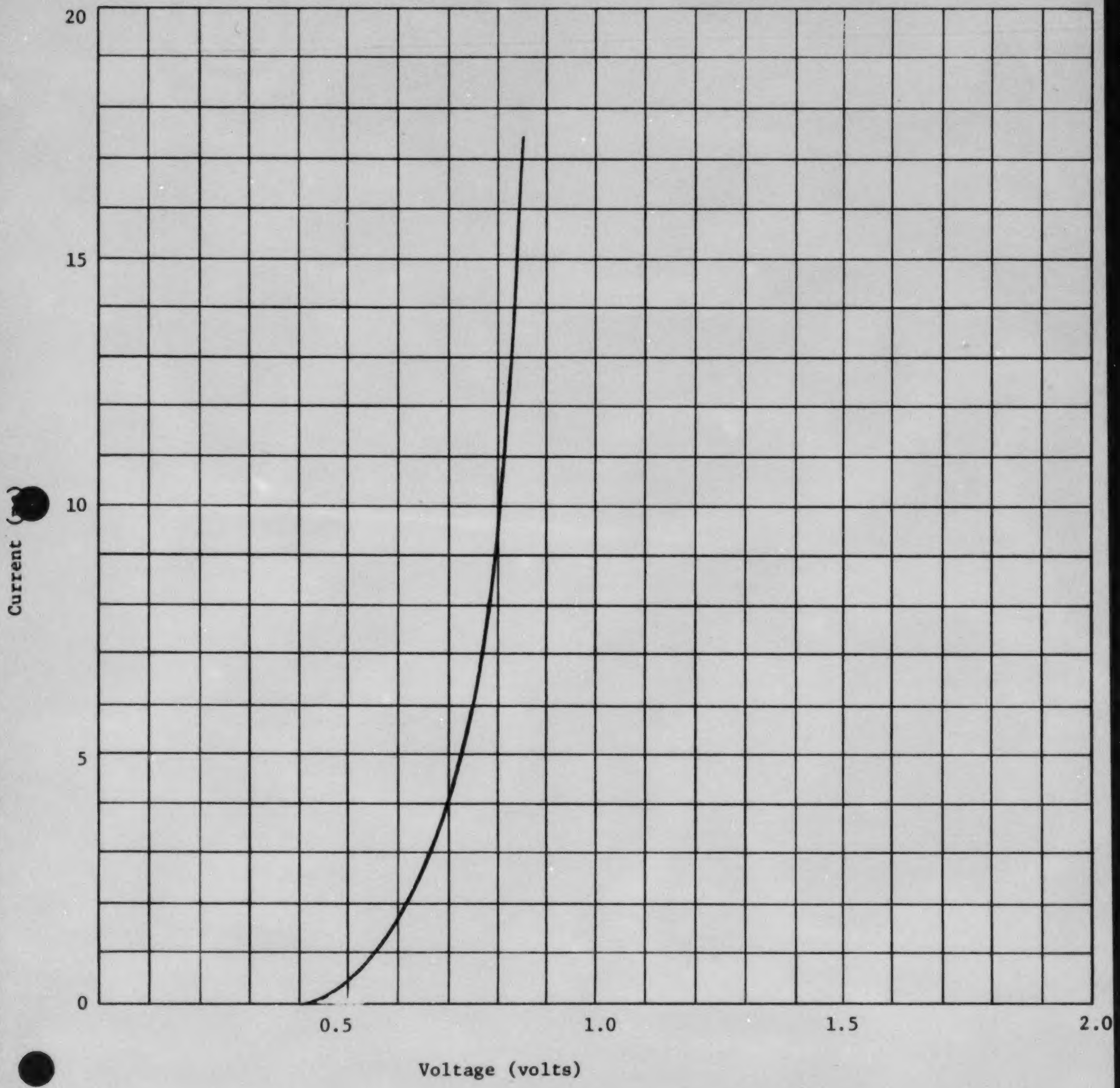


Concluding Discussion:

In later work, a graphical approach as well as an analytical approach will be used to solve transistor circuits.

Current - Voltage Characteristic

for a Diode



Phase 5 Series Circuits

Facts and principles to be learned in this phase.

1. The current is the same through any component in a series circuit.
2. In a series circuit the sum of the voltage drops is equal to the applied voltage.
3. The total resistance in a series circuit is equal to the sum of all the resistors.

Preliminary Discussion

A series circuit is defined as one in which the current is the same at any point in the circuit. Let us consider the series circuit illustrated in Figure 1.

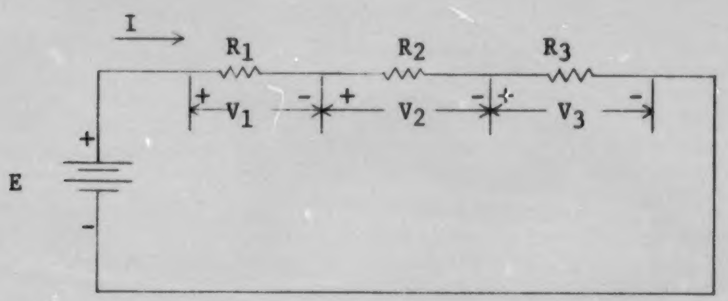


Figure 1 - Series Circuit

The voltage drop across each resistor can be computed from Ohm's law as

$$V_1 = IR_1 \qquad (1)$$

$$V_2 = IR_2 \qquad (2)$$

$$V_3 = IR_3 \qquad (3)$$

The sum of these three voltage drops must equal the applied voltage E. Therefore

$$E = V_1 + V_2 + V_3 \qquad (4)$$

Substituting equations (1), (2), and (3) into (4) yields,

$$E = IR_1 + IR_2 + IR_3$$

Factoring

$$E = I\ (R_1 + R_2 + R_3) \qquad (5)$$

Dividing both sides of equation (5) by I yields

$$\frac{E}{I} = R_1 + R_2 + R_3$$

This ratic, (the applied voltage divided by the current) is the equivalent resistance which the source sees. Therefore the total resistance which is seen by the source is $R_1 + R_2 + R_3$.

In general, for N resistors in series the total resistance R_T, is

$$R_T = R_1 + R_2 + R_3 + \dots R_N \qquad (6)$$

Laboratory Operation Procedure:

1. Measure, on an ohmmeter and on a G. R. Impedance Bridge, the values of the three following resistors; 56 ohm, 120 ohm, and 330 ohm.
2. Connect the three resistors in series, as shown in Figure 2, and with an ohmmeter and G. R. Bridge measure the resistance between points A and B.

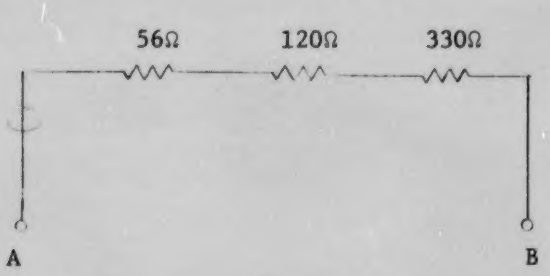


Figure 2 - Three Resistors Connected in Series

3. To the circuit of Figure 2, apply 10 volts between points A and B and measure the current which flows. Also measure V_1, V_2 and V_3. Does $E = V_1 + V_2 + V_3$?

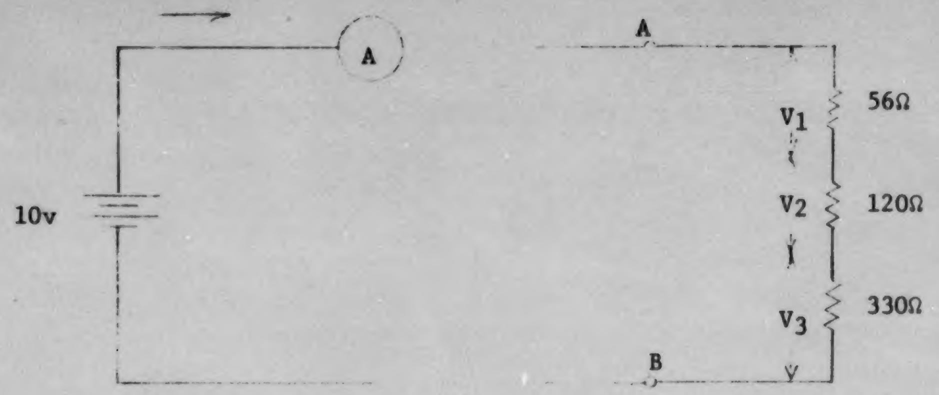


Figure 3 - Voltmeter - Ammeter Method of Obtaining Resistance

Take the ratio of the applied voltage to the current flowing $\frac{E}{I}$.

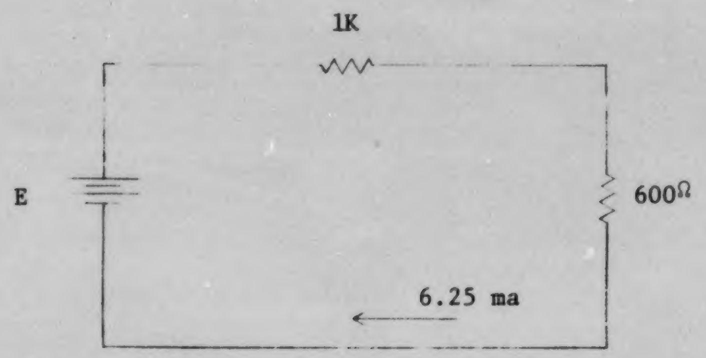
This gives the total resistance offered by this circuit.

4. Calculate the total resistance in the circuit of Figure 3 using equation (6).
5. Compare the resistance of the series circuit obtained by the Ohmmeter, the Bridge, the Ammeter - Voltmeter method and the calculated value.

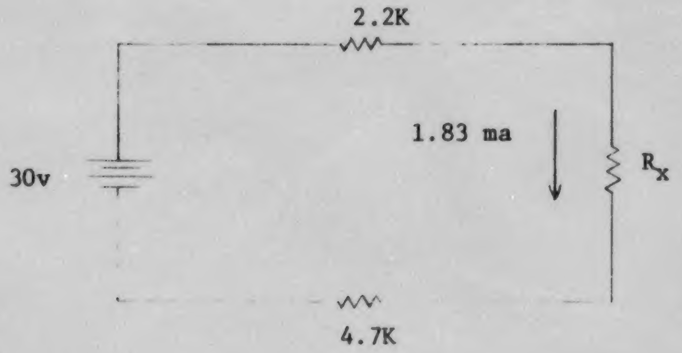
Phase 5 **Series Circuit**

Preparation Test

1. What voltage must be applied to the following circuit for the resistive network to draw 6.25 ma from the battery?


1K
E
600Ω
6.25 ma

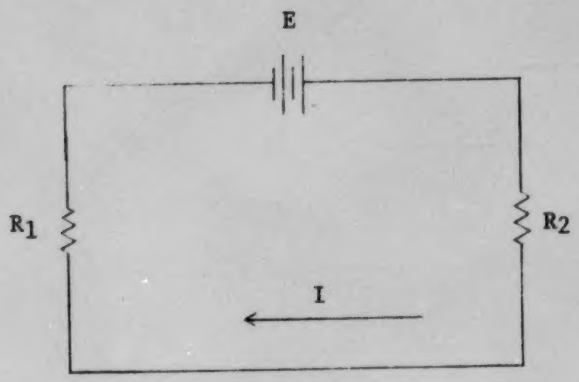
2. Determine the value of R_x for the conditions of the following circuit.


2.2K
1.83 ma
30v
R_x
4.7K

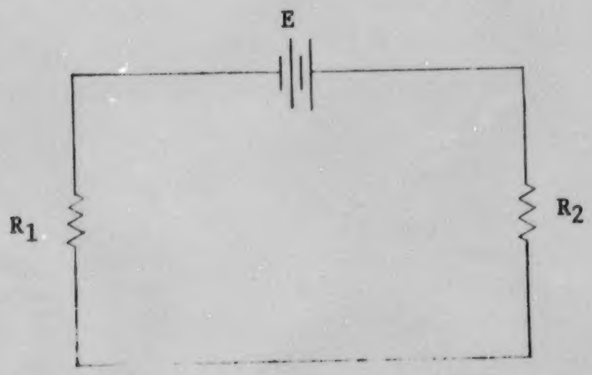
3. If $^{1}/3$ of the applied voltage is dropped across R_1 and the remaining voltage is dropped across R_2.

a) Express E in terms of I, R_1, and R_2.

b) Express R_2 in terms of E and I.



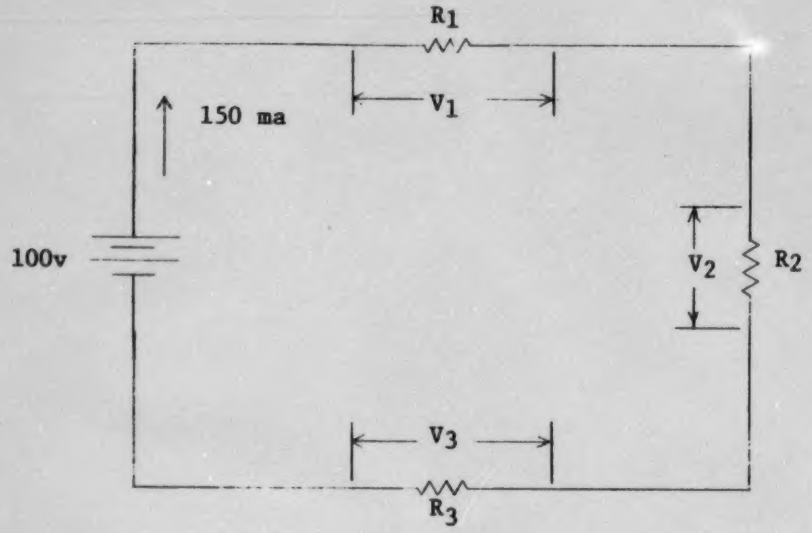
4. Express the voltage across each resistor in terms of E, R_1, and R_2.



Phase 5 **Series Circuit**

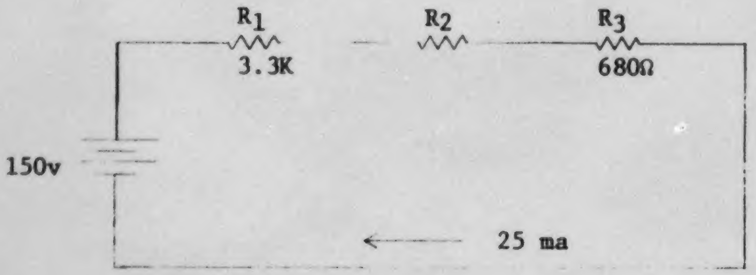
Homework Exercises

1. Determine R_1, R_2, R_3 in the circuit shown below, if the following conditions exist: I_T = 150 ma, V_1 = 25 volts, V_2 = 60 volts, V_3 = 15 volts.



R_1
V_1
150 ma
100v
V_2
R_2
V_3
R_3

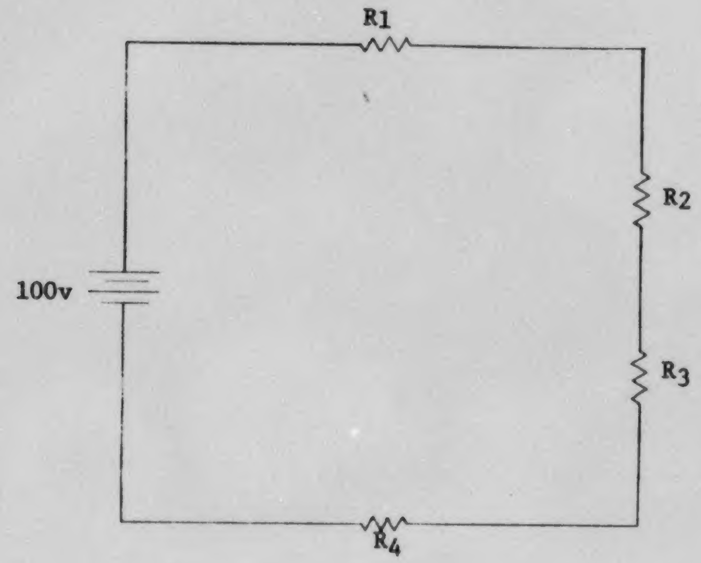
2. What is the value of R_2 in the following circuit?



R_1
3.3K
R_2
R_3
680Ω
150v
25 ma

3. Complete the following table for the circuit shown below.

	R	V	I
R_1		15v	
R_2	200Ω		
R_3			50 ma
R_4		35v	


R1
R2
100v
R3
R4

Concluding Discussion:

In a series circuit the voltage drop across a given resistor is directly proportional to that resistance. Although series circuits are seldom encountered in practice, it is essential that the technician learn about it before proceeding to more complex circuits.

Phase 6 Parallel Circuits

Facts and principles to be learned in this phase

1. In a parallel circuit, the voltage across each component is the same.
2. The sum of the branch currents is equal to the total current entering the parallel network.
3. The total resistance offered by a parallel network is given by

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots \frac{1}{R_n}} ,$$

for n branches.

Preliminary Discussion:

A parallel circuit is defined as one in which the voltage is common to all the branches in the circuit. Let us consider the simple parallel circuit of Figure 1.

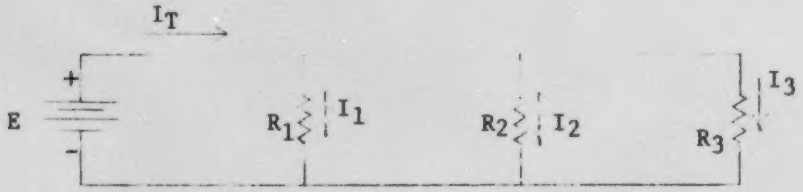


Figure 1 - Parallel Circuit

Since the voltage is the same across each resistor, the branch currents are

$$I_1 = \frac{E}{R_1} \quad (1)$$

$$I_2 = \frac{E}{R_2} \quad (2)$$

$$I_3 = \frac{E}{R_3} \quad (3)$$

The total current (I_T), provided by the battery is equal to the sum of the three branch currents: This is expressed as,

$$I_T = I_1 + I_2 + I_3 \qquad (4)$$

Substituting equations (1), (2), and (3) into (4) yields equation (5).

$$I_T = \frac{E}{R_1} + \frac{E}{R_2} + \frac{E}{R_3} \qquad (5)$$

Factoring

$$I_T = E \quad \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \qquad (6)$$

Solving for $\frac{E}{I_T}$ yields

$$\frac{E}{I_T} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} \qquad (7)$$

Thus the total opposition (resistance) offered by this parallel circuit is,

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} \qquad (8)$$

or putting equation (8) into the form below,

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \qquad (9)$$

Laboratory Operation Procedure:

1. Use the same three resistors as in Phase 5 and connect them in parallel.
2. Determine the resistance by the four methods that we used in Phase 5 and compare.
3. Construct the circuit of Figure 2 and measure the branch currents and total current. Does $I_T = I_1 + I_2 + I_3$?

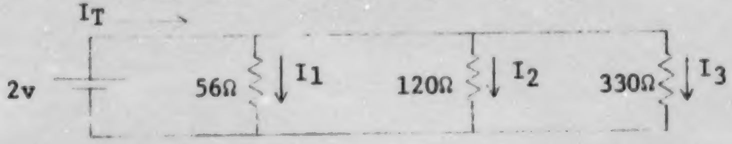
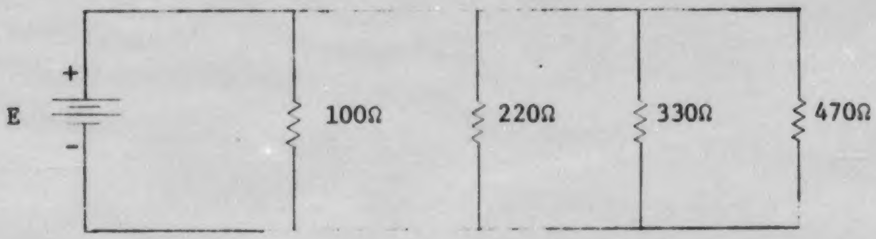


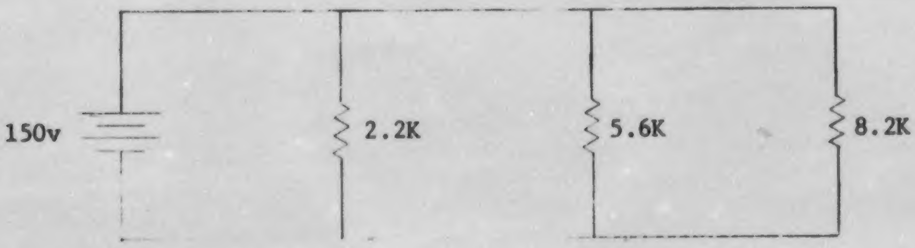
Figure 2

Preparation test:

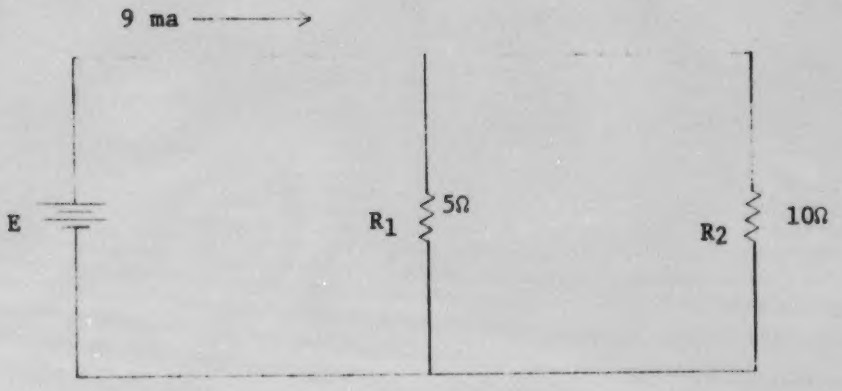
1. What is the total resistance seen by the battery in the following circuit?


+
E
-
100Ω
220Ω
330Ω
470Ω

2. What current is delivered by the battery in the following circuit?

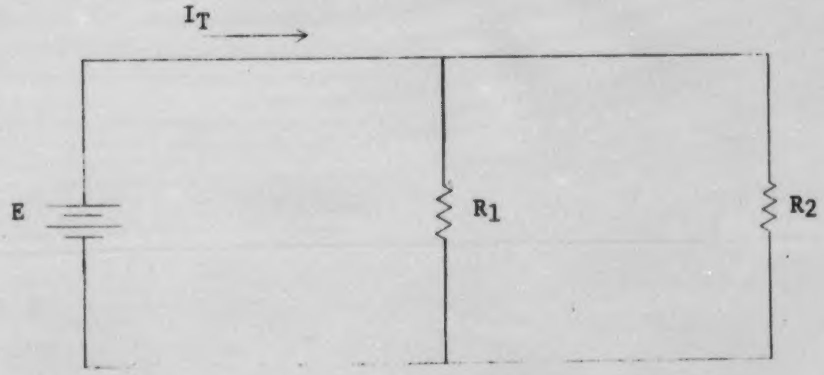

150v
2.2K
5.6K
8.2K

3. What is the current in each branch of the following circuit?


9 ma
E
R_1
5Ω
R_2
10Ω

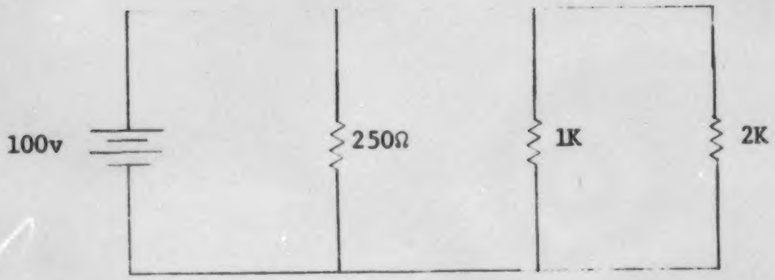
4. a) Express the current through R_1 in terms of I_T, R_1, and R_2.

b) Express R_2 in terms of I_1, I_2, and R_1.

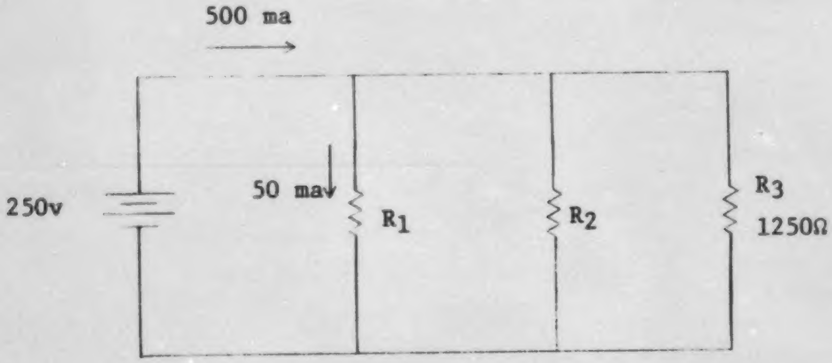


Homework Excercises

1. What current is delivered by the battery in the following circuit?

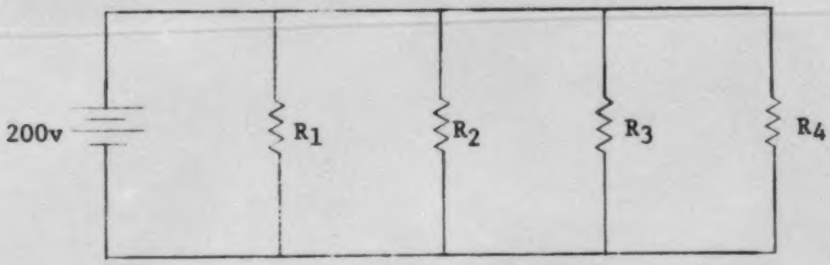

100v
250Ω
1K
2K

2. What is the value of R_2 in the following circuit?


500 ma
250v
50 ma
R_1
R_2
R_3
1250Ω

3. Complete the following table for the circuit shown below.

	R	V	I
R_1			30 ma
R_2	5K	200v	
R_3			15 ma
R_4	2K		


200v
R_1
R_2
R_3
R_4

Concluding Discussion:

It should be concluded that the total current in a parallel circuit is equal to the sum of the individual branch currents.

Power

Facts and principles to be learned in this phase

1. Concept of power
2. Power developed in a component is equal to the product of current and voltage.
3. Power dissipated by a device is actually the transformation of electrical energy into heat energy.

Preliminary Discussion:

One of the most important quantities which one is concerned with is the power that a component or device is able to dissipate. Thus it is vital that an engineering technician be able to make power measurements and calculations.

Discussion:

Energy is the ability to do work. The basic unit for energy in the MKS system is the joule. Power, having the watt as its basic unit, is the rate of doing work. One watt of power is developed when energy is expended at the rate of 1 joule per second. The power developed in a resistive circuit is given by the expression,

$$P = E \times I \qquad (1)$$

To prove that power has the watt for its unit, let us perform dimensional analysis on equation (1).

Since the basic definitions of the volt and the ampere are,

$$\text{Volt} = \frac{\text{joule}}{\text{coulomb}} \qquad \text{Ampere} = \frac{\text{coulomb}}{\text{second}} \;,$$

then

$$P = E \times I = \frac{\text{joule}}{\text{coulomb}} \times \frac{\text{coulomb}}{\text{second}} = \frac{\text{joule}}{\text{sec.}}$$

and from the above, a joule per second is a watt.

In general, the power developed in a resistor is given by equation (1).

$$P = E \times I \qquad (1)$$

and since from ohm's law

$$E = IR$$

then it follows that

$$P = IR \times I = I^2R \qquad (2)$$

and also

$$P = E \times \frac{E}{R} = \frac{E^2}{R} \qquad (3)$$

Therefore we have three expressions for the power dissipated in a resistor. The power dissipated by a resistor or a device is actually the transformation of electrical energy into heat energy. As power is dissipated in a component or a device, heat is given off to the surrounding air. If the component or device develops heat more rapidly than it can give it off, the temperature of the component or device will rise to a value such that a balance is achieved. If the temperature is at too high a value, the component or device may be destroyed or its characteristics may be changed. It therefore seems logical that the physical size of the component or device has a lot to do with its power rating, and in general, the greater its physical size the greater will be its power rating.

Laboratory Operation Procedure:

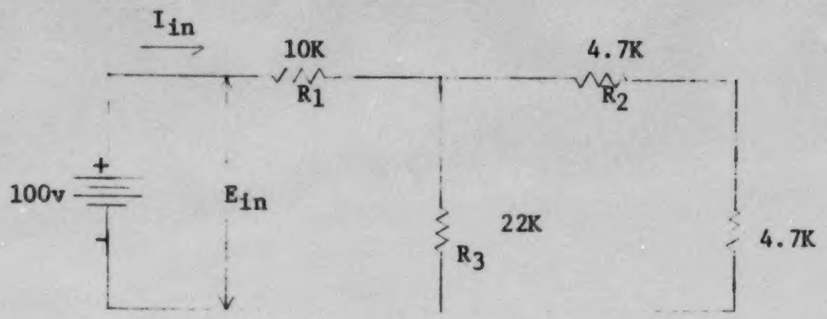


Figure 1

1. Obtain and measure the value of the four resistors indicated in Figure 1.
2. Using these values calculate current through and voltage across each resistor.
3. Calculate the power dissipated in each resistor, and the total power.
4. Set up the circuit in Figure 1.
5. Measure and record the voltage drops across each resistor using one voltmeter.
6. Measure and record the current flowing through each resistor using one ammeter.
7. Measure line voltage and line current.
8. Calculate power developed in each resistor and the total power supplied.
9. Compare the theoretical with the actual results.

Phase 7 **Power**

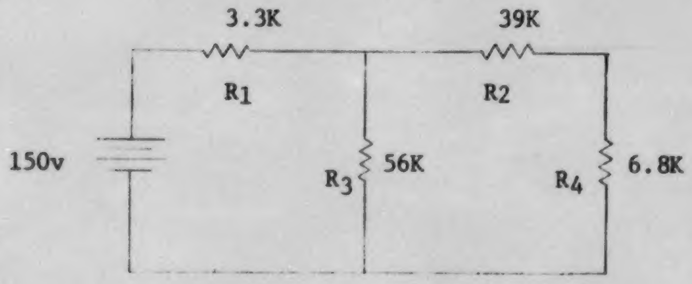
Preparation Test:

1. What voltage must be connected to a 470Ω resistor so that 1.2 watts are dissipated?

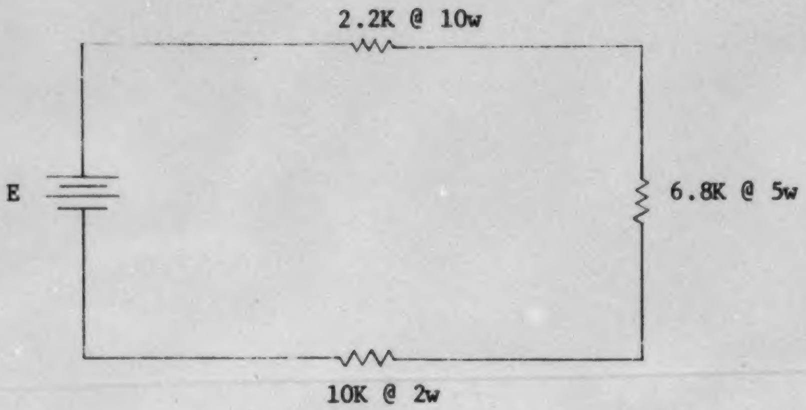
2. What current flows through and 820 ohm resistor which dissipates 1 watt of power?

3. What must the power rating be of a 12 kilohm resistor connected across a 50 volt source?

4. What is the power dissipated by each resistor in the following circuit?



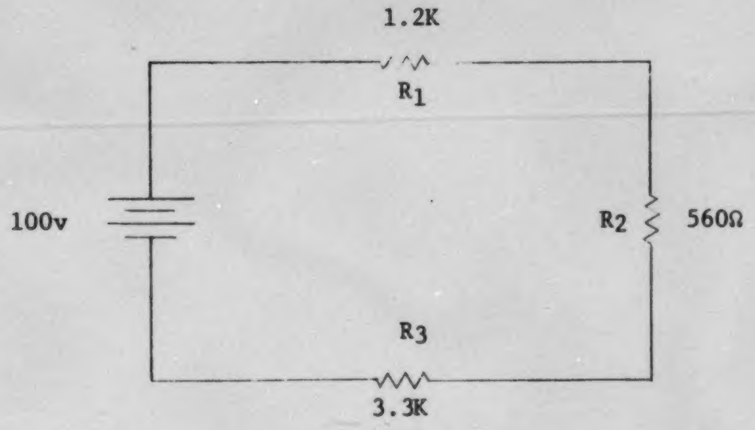
5. What is the maximum voltage that can be applied to the following circuit, so that none of the power ratings are exceeded?


2.2K @ 10w
E
6.8K @ 5w
10K @ 2w

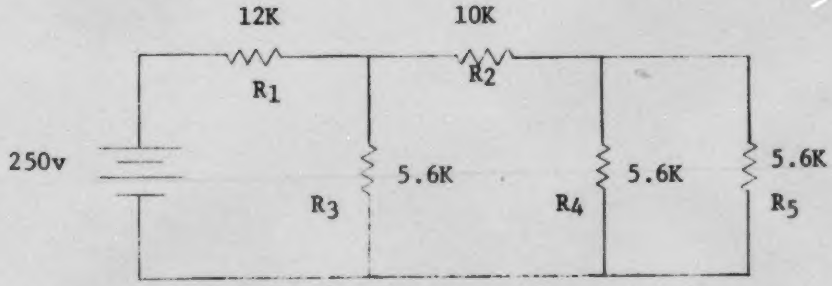
Homework Excercises:

Calculate the voltage across, current through, and power dissipated by each resistor in the following circuits.

1.


1.2K
R1
100v
R2
560Ω
R3
3.3K

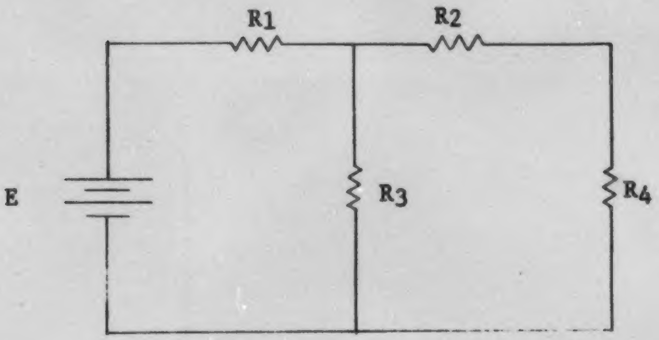
2.


12K
10K
R1
R2
250v
5.6K
R3
5.6K
R4
5.6K
R5

3. Complete the following table for the circuit shown below. What is the battery voltage?

	R	V	I	P
R_1	22K		7.5ma	
R_2	3.3K			
R_3			2.5ma	
R_4				2.5w

E =



Concluding Discussion:

Later, when one is designing an amplifier, we will see that power calculations will have to be made so that the transistor is not damaged or destroyed.

Phase 8 Maximum Power Transfer

Facts and principles to be learned in this phase

1. Internal resistance of power supply must be considered in any calculations.
2. Maximum power transfer occurs when load is matched to internal resistance of power supply.
3. Two laboratory procedures for determining internal resistance.

Preliminary Discussion:

Every practical generator has an internal resistance. As current is drawn from the generator the terminal voltage of the generator drops due to the drop across the internal resistance. In addition to causing the terminal voltage to drop as current is drawn from the source, the internal resistance places an upper limit on the current which the generator can deliver and therefore there is a limit to the power which a generator can deliver. This phase is concerned with the Principle of Maximum Power Transfer.

Discussion:

An equivalent circuit for a practical generator consists of an ideal source in series with a resistance (R_X). An ideal source is a source capable of developing a constant voltage at any current. The resistance R_X is the internal resistance of the source. A schematic for this equivalent circuit is shown in Figure 1.

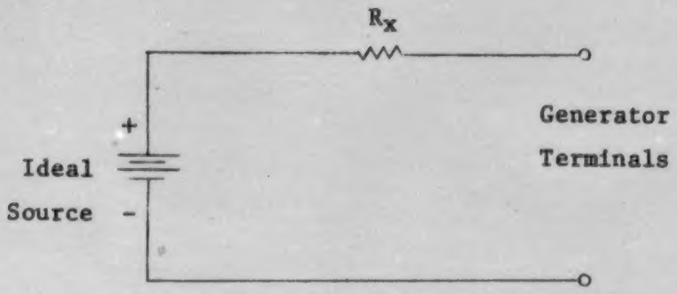


Figure 1 - Equivalent Circuit for a Practical Generator

In order to determine the effect of connecting different load resistances to a practical generator, let us consider Figure 2.

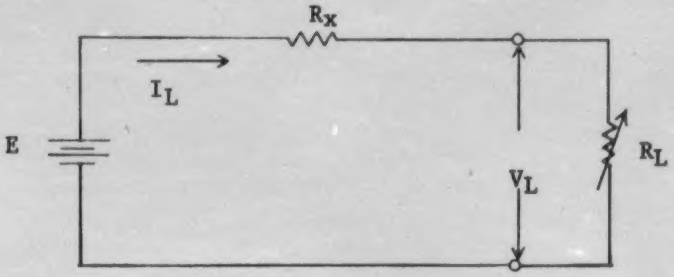


Figure 2

Let us determine the power delivered to the load R_L.

$$P_L = I_L{}^2R_L \qquad (1)$$

but

$$I = \frac{E}{R_L + R_x};$$

hence

$$P_L = \frac{E2R_L}{(R_L + R_x)^2} \qquad (2)$$

We will now proceed to determine the value of R_L which will dissipate the largest amount of power.

To normalize equation (2), divide numerator and denominator by R_x. This results in equation (3)

$$P_L = \frac{E^2 \frac{R_L}{R_x}}{\left(1 + \frac{R_L}{R_x}\right)^2} \qquad (3)$$

Table I contains data which was calculated using equation (3)

R_L/R_x	0	0.5	1	1.5	2.0	2.5	3.0	3.5	4.0
P_L	0	$.222E^2$	$.25E^2$	$.24E^2$	$0.222E^2$	$0.204E^2$	$0.1875E^2$	$.173E^2$	$.16E^2$

Table I - Values of P_L for Various Values of R_L/R_x

Plotting the information in Table I results in the curve shown in Figure 3.

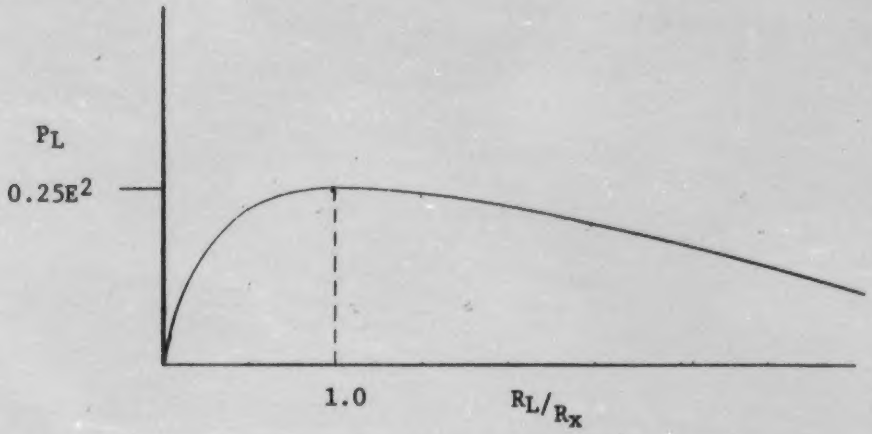


Figure 3 - Plot of P_L versus R_L/R_x

From Figure 3, we see that maximum power is delivered to the load, when $\frac{R_L}{R_x} = 1$, or when $R_L = R_x$. Therefore in general when R_x is fixed at some value, maximum power will be transferred to a load when we choose a load equal to the internal resistance of the generator. When this is done, the terminal voltage of the generator becomes one-half of its open circuit voltage and the load current becomes one-half of the short circuit current.

Having established this, we can also use this procedure to determine the internal resistance of a given source.

Laboratory Operation Procedure:

The internal resistance of the Wentworth Power Supply will be determined by two methods.

Method 1:

Set the power supply at 100 volts, (open circuit). Attach a potentiometer across the P.S. and vary it until one-half, (50 volts), appears across the potentiometer. Disconnect and measure the resistance of the potentiometer. This is the value of R_X.

Method 2:

Set the Wentworth P.S. at 100 volts with no load (infinite R_L). Using the circuit of Figure 2, vary R_L in reasonable steps and record the voltage across the load and current through the load. Insure that R_L has a sufficient wattage rating. Repeat for the Power Supply set at 200 and 300 volts (no-load). Plot the load voltage versus load current on graph paper. This will result in a family of curves similar to the ones shown in Figure 4.

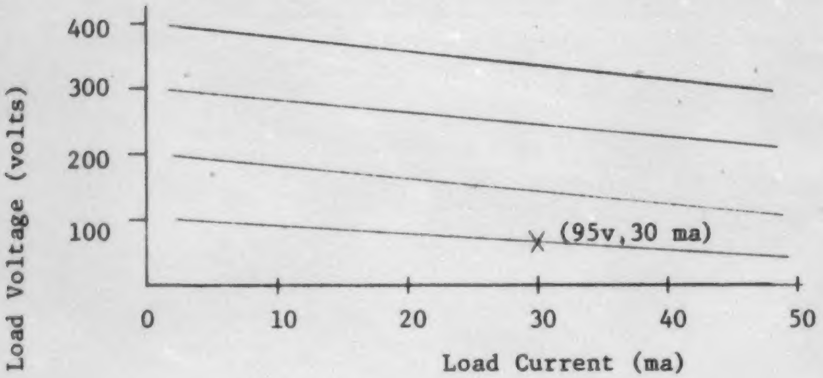


Figure 4 - Plot of Load Voltage versus Load Current

The internal resistance of the power supply can be determined from these curves in the following manner. Suppose we wish to determine the internal resistance of the power supply at 95v and 30ma. With no load the voltage is 100 volts. When the load is drawing 30ma, the voltage has dropped to 95 volts. Therefore the drop across the internal resistance is 5 volts and the internal resistance has a value of 5 volts divided by 30ma or,

$$R_x = \frac{5v}{0.03ma} = 167 \text{ ohms.}$$

We see that R_x can be determined by taking the slope of the VI curve.

Using the 100 volt curve, obtain the internal resistance at approximately 75ma by taking the slope of the curve.

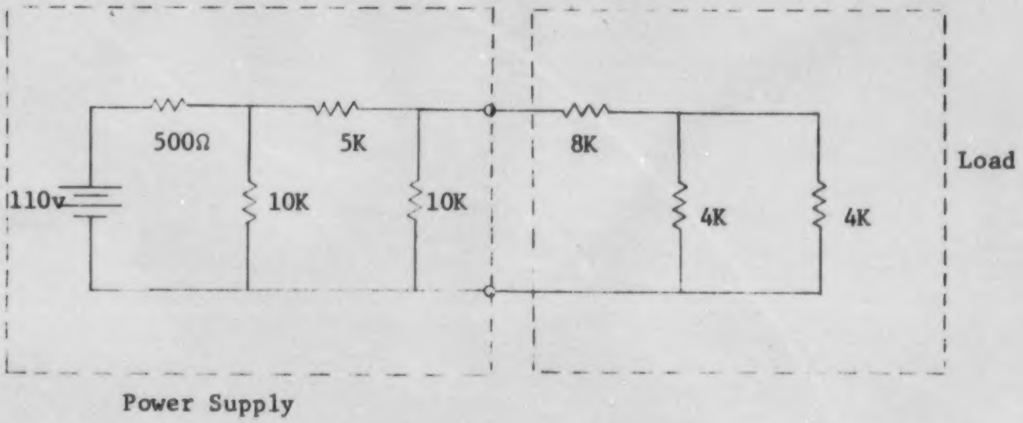
Phase 8 **Maximum Power Transfer**

Preparation Test

1. If the internal resistance of a 250 volt (open circuit) power supply is 300 ohms, what is the voltage across a 10 kilohm load when connected across is?

2. If a power supply has a terminal voltage of 24 volts when a 50 ohm load is connected across it, what is the internal resistance and open circuit voltage of the power supply if the terminal voltage is 23 volts with a 25Ω load connected across it?

3. For the following circuit, determine the input power, the output power, the efficiency, and the load resistance to give maximum power transfer.



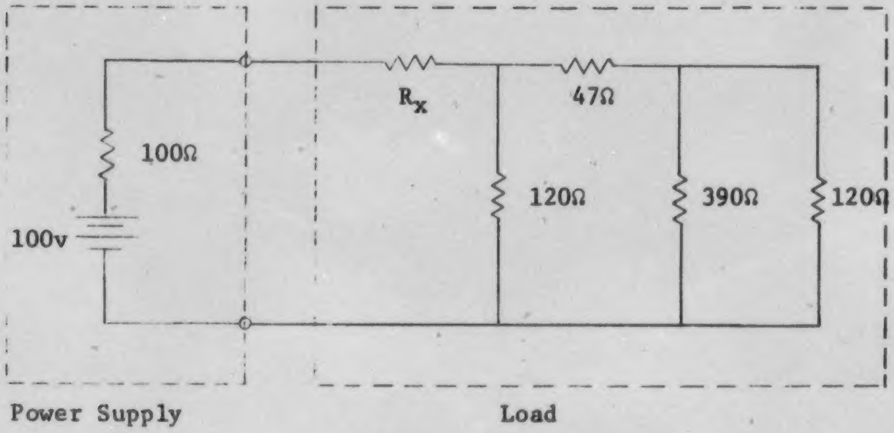
60

Phase 8 Maximum Power Transfer

Homework Exercises:

1. A battery has a terminal voltage of 100 volts when a 2 amp current is drawn from it. When the load is decreased so that a three amp current flows, the terminal voltage is 98 volts. What is the internal resistance of the battery?

2. What value of R_x, in the following circuit will give maximum power transfer?



R_x
47Ω
100Ω
120Ω
390Ω
120Ω
100v
Power Supply
Load

Concluding Discussion:

The maximum power theorem will be very valuable in the design of power amplifiers. We will now proceed to solve more complex circuits with the use of loop and nodal equations.

Loop and Nodal Analysis

Facts and principles to be learned in this phase.

1. Electrical circuits can readily be analyzed by either loop analysis or nodal analysis.
2. Any circuit may be analyzed by either method, but one or the other may save work for a given network.

Preliminary Discussion:

Passive electrical circuits are made up of resistors, inductors, and capacitors connected in some fashion and excited by sources of energy. In analyzing an electric circuit, it is usually necessary to determine the branch currents and branch voltages when the sources and component values are known. Electrical circuits can readily be analyzed by either of two systematic treatments:

A. loop analysis

B. nodal analysis

Any given circuit may be analyzed by either method, but one or the other may save work for a given network.

Both of these methods will be applied in this problem.

In order to solve a network, we must in general satisfy Kirchhoff's Voltage Laws, Kirchhoff's Current Laws, and the current-voltage relation of each component.

The two Kirchhoff's laws are stated as follows:

A. Kirchhoff's Voltage Law - The algebraic sum of voltages around any closed loop of a circuit is zero.

B. Kirchhoff's Current Law - The algebraic sum of current flowing into any node of a circuit is zero.

As an example, let us consider the simple circuit in Figure 1.

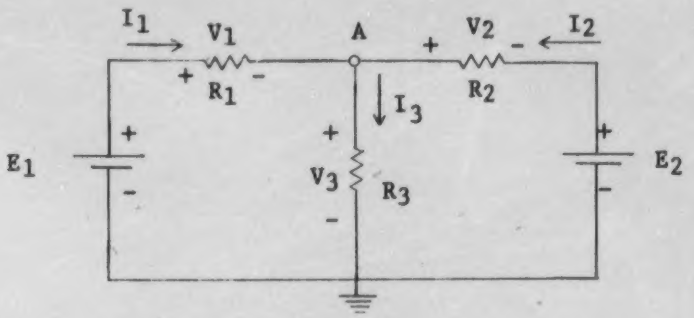


Figure 1 - Simple Circuit to be Analyzed
by the Loop and Nodal Methods

In the diagram we have defined six variables, a voltage and current for each resistor. Thus we need six independent equations in order to solve for these variables.

As stated earlier, we must in general satisfy Kirchhoff's Voltage Law, Kirchhoff's Current Law, and component relations. By inspection the two KVL equations are;

$$E_1 = V_1 + V_3 \qquad (1)$$

$$E_2 = V_2 + V_3 \qquad (2)$$

Note that applying KVL around the outer loop yields,

$$E_1 - E_2 = V_1 - V_2$$

This does not give any added information since this equation can be obtained by subtracting equation 2 from equation 1.

Now applying KCL at node A yields,

$$I_1 + I_2 = I_3 \qquad (3)$$

Also note that applying KCL at the other node, (ground node), does not yield a different equation.

The three component relations are;

$$V_1 = I_1R_1 \quad (4)$$

$$V_2 = I_2R_2 \quad (5)$$

$$V_3 = I_3R_3 \quad (6)$$

We now have six equations with six unknowns. Solving these six equations simultaneously will solve the circuit. We can save ourselves a lot of work if we define the variables in a somewhat different way that above. Let us first consider solving the above network by the loop analysis method. Instead of defining six unknowns, let us define two loop currents as shown in Figure 2.

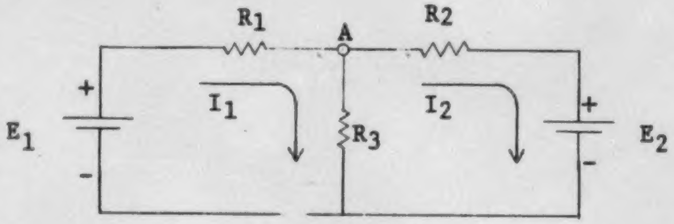


Figure 2 - Circuit of Figure 1 With Assigned Loop Currents

These loop currents automatically satisfy KCL equations. This is readily seen by summing the currents flowing into node A,

$$I_1 - I_2 + I_2 - I_1 = 0$$

thus KCL is satisfied.

Now we need only write KVL around both loops resulting in equations 7 and 8.

$$E_1 = I_1R_1 + I_1R_3 - I_2R_3 \quad (7)$$

$$-E_2 = -I_1R_3 + I_2R_3 + I_2R_2 \quad (8)$$

Where we have introduced the component relations directly into KVL equations as we went along.

Combining like terms in equations 7 and 8 results in,

$$E_1 = I_1 (R_1 + R_3) - I_2 R_3 \qquad (9)$$

$$-E_2 = -I_1 R_3 + I_2 (R_2 + R_3) \qquad (10)$$

Now solving equations 9 and 10 simultaneously yields I_1 and I_2. Using the components relations, we can find the voltage drop across each resistor. Note that we arbitrarily assumed the direction of I_1 and I_2. A negative I_1 or I_2 simply means that we were wrong in our assumption and the current is actually flowing in the opposite direction to that assumed.

The nodal analysis for this circuit is as follows:

First we define a datum (reference) node and define each unknown node voltage with respect to the datum node. These voltages will automatically satisfy KVL. This can easily be seen from our example:

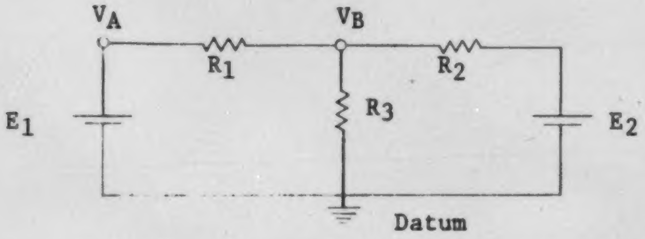


Figure 3 - Circuit of Figure 1 to be Analyzed by Nodal Analysis

$$V_A - (V_A - V_B) + V_B = 0$$

We now need only write KCL equation at each node, in terms of component equations using the voltage variables already defined. This method results in only one equation (11).

$$\frac{V_B}{R_3} + \frac{V_B - E_1}{R_1} + \frac{V_B - E_2}{R_2} = 0 \qquad (11)$$

After this equation is solved for the one unknown (V_B), we can then use the component relations to solve the rest of the network. Note that for this particular circuit, the nodal method gave the easier solution since we had to only solve one equation. This is not always so. And as an example let us consider the circuit in Figure 4. We will solve for the current in the 60 ohm resistor by both methods.

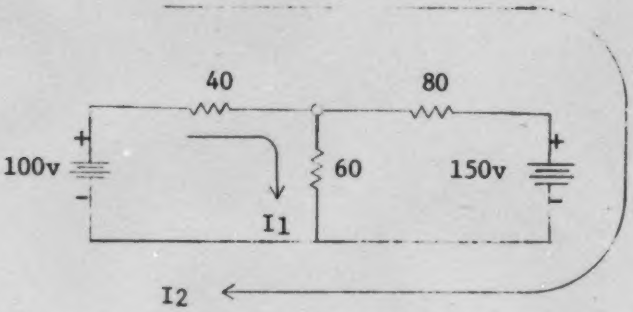


Figure 4 - Circuit to be Solved by Loop Analysis

We have defined two loop currents I_1 and I_2 as shown. The currents are defined in this manner so that we need only solve for I_1 in order to obtain the current through the sixty ohm resistor.

Tracing around both loops, we obtain the following two equations;

$$100 = I_1\ (40) + I_1\ (60) + I_2\ (40) \qquad (12)$$

$$100 - 150 = I_1\ (40) + I_2\ (40) + I_2\ (80) \qquad (13)$$

Combining like terms,

$$100 = I_1\ (100) + I_2\ (40) \qquad (14)$$

$$-50 = I_1\ (40) + I_2\ (120) \qquad (15)$$

Solving these two equations simultaneously for I_1 results in

$$I_1 = 1.348 \text{ amps.}$$

We will now solve for the current through the 60 ohm resistor be nodal analysis. Summing the currents at node A results in,

$$\frac{V_A - 100}{40} + \frac{V_A}{60} + \frac{V_A - 150}{80} = 0 \qquad (16)$$

Solving for V_A results in

$$V_A = 80.9 \text{ volts}$$

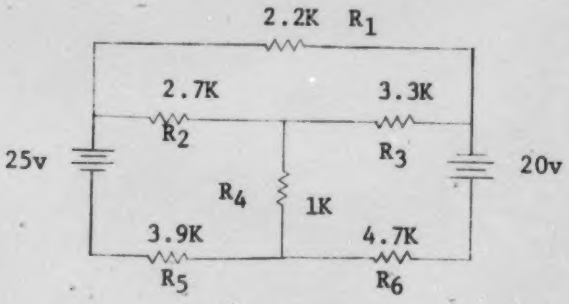
The current through the 60 ohm resistor is then

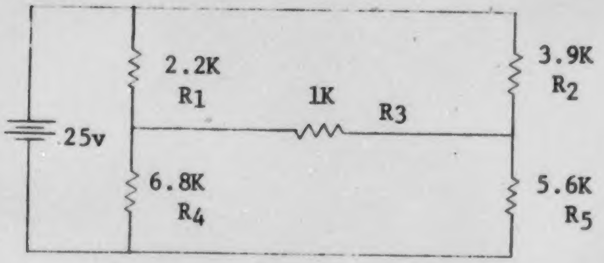
$$I = \frac{V_A}{60} = \frac{80.9}{60} = 1.348 \text{ amps.}$$

Laboratory Operation Procedure:

For the following circuits,

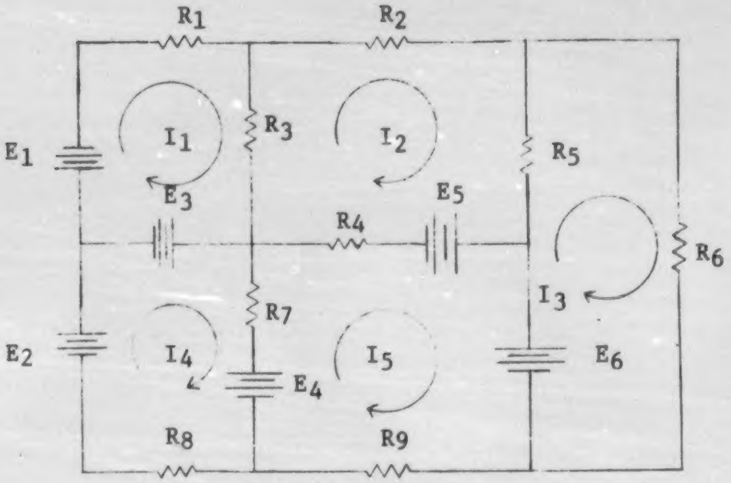
1. Solve for the currents and voltages designated by
   (a) loop analysis and
   (b) nodal analysis.
2. Determine the value of the resistors on the G.R. bridge.
3. Set up each circuit and measure the currents and voltages of each resistor.
4. Compare the theoretical results with the experimental results and determine the % error.


2.2K R1
2.7K
3.3K
R2
25v
R3
20v
R4
1K
3.9K
4.7K
R5
R6


2.2K
R1
3.9K
R2
1K
R3
25v
6.8K
R4
5.6K
R5

Preparation Test:

1. Make the necessary corrections in the loop equations for the following circuit.


R1
R2
R3
R5
E1
I1
I2
E3
E5
R4
R6
I3
R7
E2
I4
E4
I5
E6
R8
R9

$-E_1 - E_3 = I_1 (R_1 + R_3) + I_2 R_3$

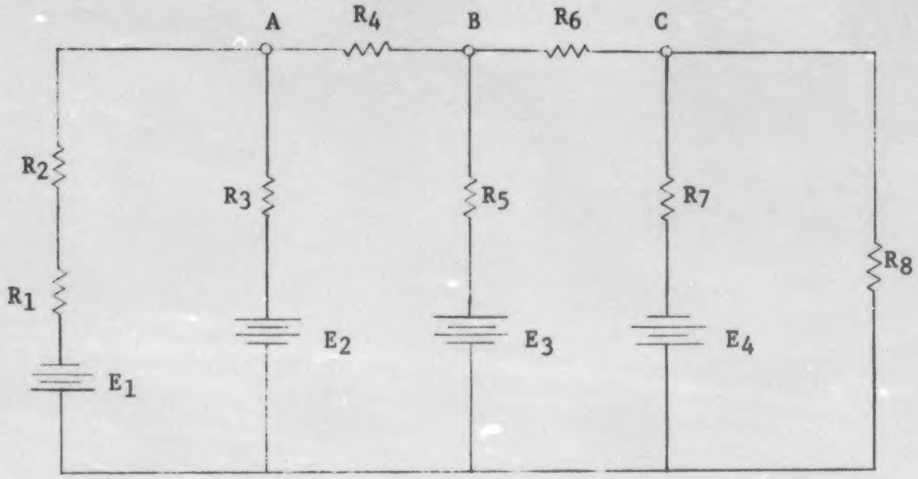
$E_5 = -I_1 (R_3) + I_2 (R_2 + R_3 + R_4) - I_3 (R_5) - I_5 (R_4)$

$E_6 = -I_2 (R_5) + I_3 (R_5 + R_6) - I_5 (E_6)$

$E_2 + E_3 - E_4 = I_4 (R_7 + R_8) - I_5 (R_7)$

$E_4 + E_5 + E_6 = -I_2 (R_4) + I_4 (R_7) + I_5 (R_4 + R_7 + R_9)$

2. Make the necessary corrections in the nodal equations for the following circuit.


A
R4
B
R6
C
R2
R3
R5
R7
R8
R1
E2
E3
E4
E1

$$\frac{V_A - E1}{R_1 + R_2} + \frac{V_A - E2}{R_3} + \frac{V_A - V_B}{R_4} = 0$$

$$\frac{V_B - V_A}{R_4} + \frac{V_B - E3}{R_5} + \frac{V_B + V_c}{R_6} = 0$$

$$\frac{V_B - V_c}{R_6} + \frac{V_c - E4}{R_7} + \frac{V_c}{R_8} = 0$$

Loop and Nodal Analysis

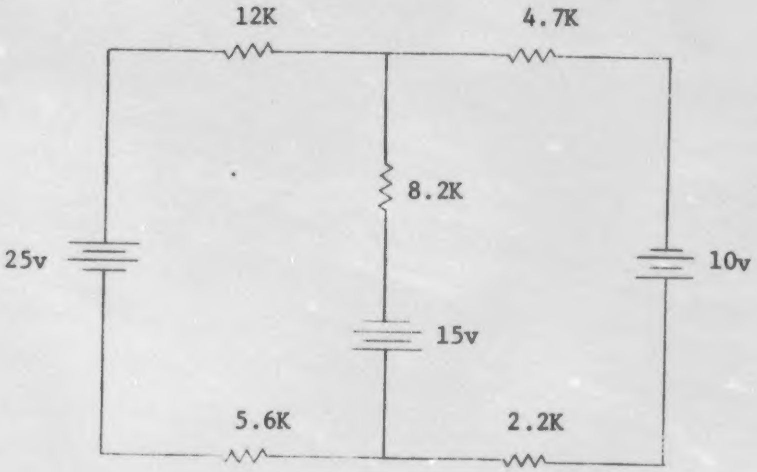
Homework Exercises:

For the following circuits, solve for the current through and the voltage across each resistor by:

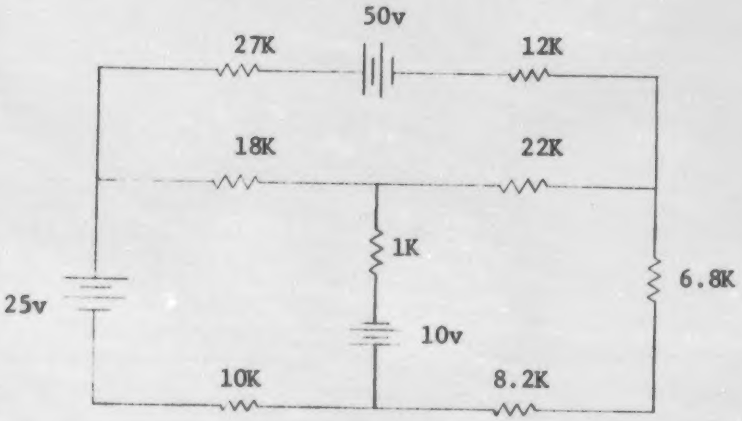
A. loop analysis

B. nodal analysis.

1.


12K
4.7K
8.2K
25v
10v
15v
5.6K
2.2K

2.


50v
27K
12K
18K
22K
1K
6.8K
25v
10v
10K
8.2K

Concluding Discussion:

The two systematic treatments for solving electrical networks, namely loop analysis and nodal analysis are very valuable when analyzing complex circuits.

In some of the later phases we will introduce some theorems, such as Norton's, and Thevenin's. These theorems are also useful for analyzing complex circuits.

Facts and principles to be learned in this phase.

1. Application of Thevenin's Theorem.

Preliminary Discussion:

In many cases, a network can be analyzed more easily by applying some network theorems. These theorems are general statements some of which are applicable to all possible networks and others are restricted to networks of a limited class. Thevenin's, Norton's, and the Superposition theorems will be discussed and applied in this problem. They will be given without proof. This theorem states that a network which feeds a load R_L behaves, as far as the load is concerned, as a single voltage source in series with a single resistor. Consider the network illustrated in Figure 1. The network in the box can be simplified by Thevenin's Theorem to a voltage source (E_{TH}) in series with a resistance (R_{TH}).

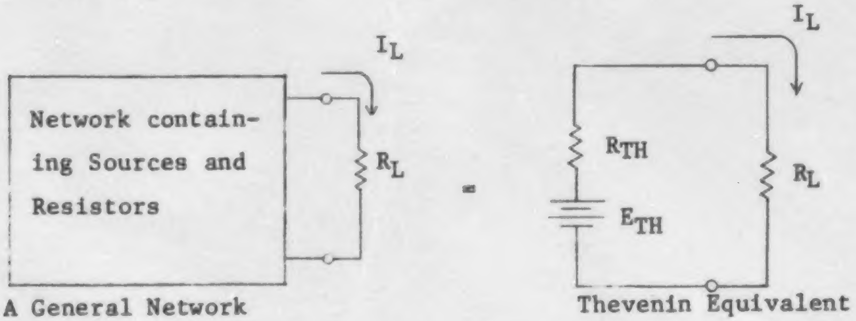
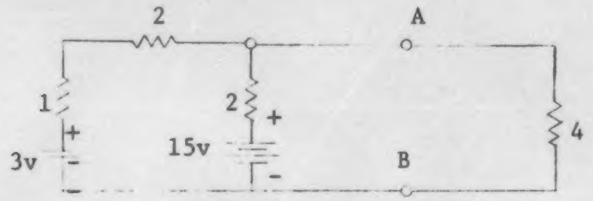


Figure 1 - General Network Simplified by Thevenin's Theorem

The Thevenin equivalent source (E_{TH}) is obtained by determining the open circuit voltage at the terminals of the original network. The Thevenin equivalent resistance (R_{TH}) is obtained by determining the resistance looking back into the network with all the sources set to zero. As an, example, suppose we consider the network shown in Figure 2. It is desired to determine the current in the 4 ohm resistor. This calculation can be simplified by reducing the circuit to the left of points A - B to its Thevenin equivalent, i.e. a single ideal source and a single resistance.



Network to be Analyzed by

Thevenin's Theorem

Figure 2

The first step in applying Thevenin's theorem is to determine the open circuit voltage at points A - B. With the aid of Figure 3 the open circuit voltage is as follows:

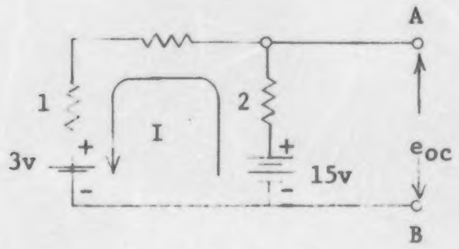


Figure 3

Solving for the current I, yields

$$I = \frac{15 - 3}{5} = \frac{12}{5}$$

$$E_{oc} = +15 - \frac{12}{5} \times 2 = 15 - 4.8 = 10.2 \text{ volts.}$$

To determine the thevenin resistance, we look into terminals A and B and set all sources to zero. This results in Figure 4.

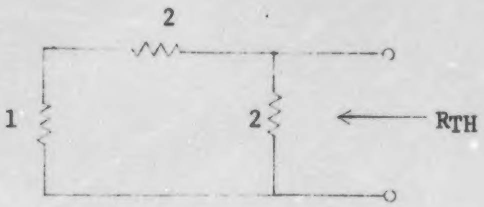


Figure 4 - Circuit to Determine Thevenin Resistance

Thus the Thevenin resistance is,

$$R_{TH} = \frac{3\ (2)}{3 + 2} = \frac{6}{5}$$

Therefore the circuit to the left of points A - B can be replaced by Thevenin's equivalent circuit consisting of a 10.2v source in series with a 1.2 ohm resistor. This is illustrated in Figure 5.

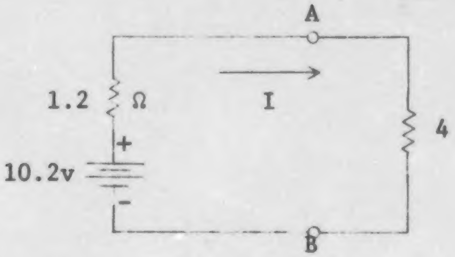


Figure 5 - Simplified Circuit after Applying

Thevenin's Theorem

The current through the 4 ohm resistor is then

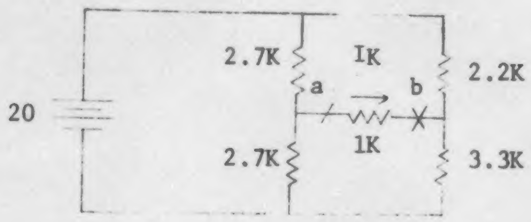
$$I = \frac{10.2}{5.2} = 1.96\ A$$

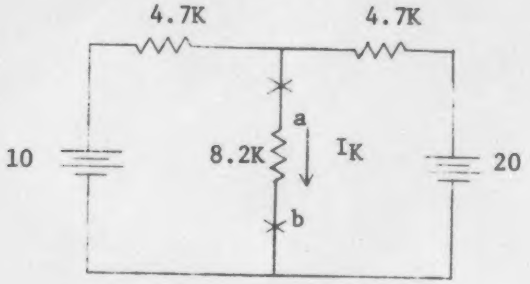
As can be seen the original network is simplified to a single loop circuit.

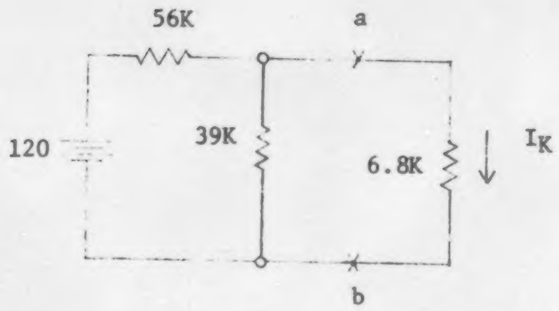
Laboratory Operation Procedure:

Determine I_K for the three circuits below by applying Thevenin's Theorem at the indicated points.

Construct each circuit and measure I_K.


20
2.7K
2.7K
a
I_K
b
1K
2.2K
3.3K

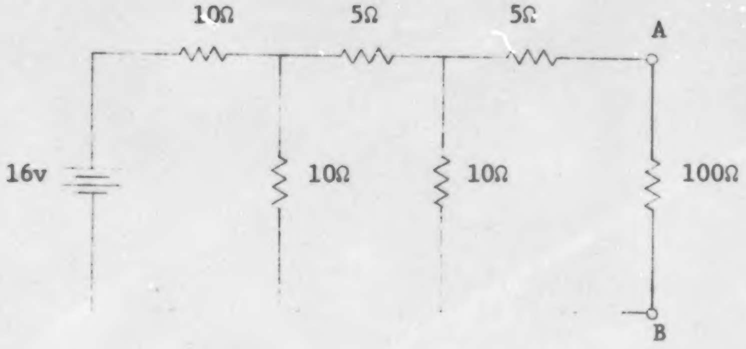

4.7K
4.7K
10
8.2K
a
I_K
b
20

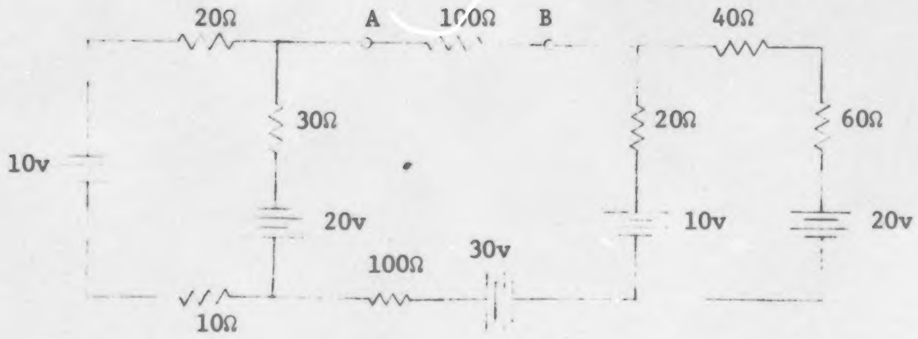

56K
a
120
39K
6.8K
I_K
b

Phase 10 **Thevenin's Theorem**

Preparation Test:

Find the Thevenin's Equivalent Circuit for the circuits shown below.

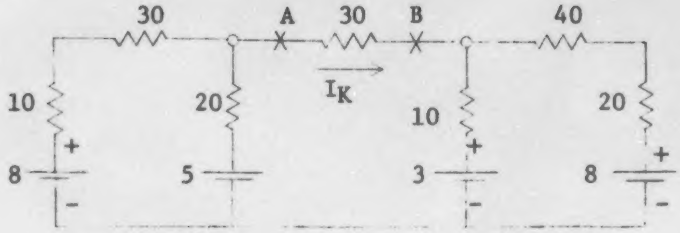

10Ω
5Ω
5Ω
A
16v
10Ω
10Ω
100Ω
B


20Ω
A
100Ω
B
40Ω
30Ω
20Ω
60Ω
10v
20v
10v
20v
100Ω
30v
10Ω

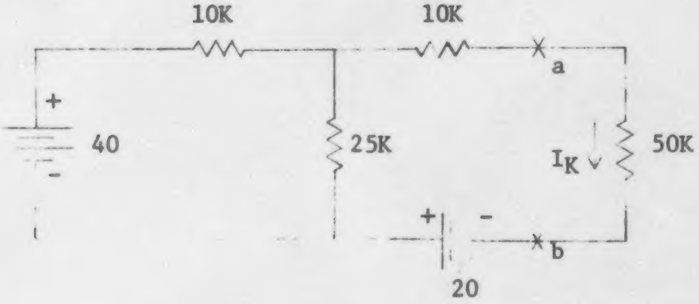
Phase 10 **Thevenin's Theorem**

Homework Exercises:

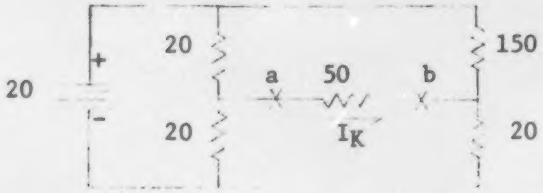
In the following networks, solve for I_K by applying Thevenin's Theorem at points A - B.



30
A
30
B
40
I_K
10
20
10
20
+
8
-
5
+
3
-
8
+
-



10K
10K
a
+
40
-
25K
I_K
50K
+
-
b
20



20
+
-
20
20
a
50
b
I_K
150
20

78

Concluding Discussion:

Application of Thevenin's theorem to any complex networks generally simplifies the network to a much simpler circuit. Although the circuit could be solved by loop or nodal analysis, it is sometimes easier to solve the network by applying Thevenin's theorem. The next phase will deal with Norton's theorem, another simplifying theorem.

Phase 11 Norton's Theorem

Facts and principles to be learned from this phase.

1. Application of Norton's theorem.

Preliminary Discussion:

Norton's Theorem replaces a given network with a constant current source in parallel with a single resistor.

Consider the network of Figure 1A once again. This is repeated in Figure 1A with the Norton Equivalent illustrated in Figure 1B.

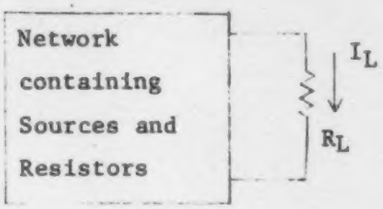


Figure 1A

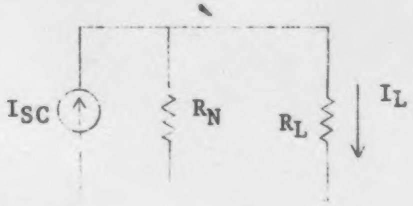


Figure 1B - Norton Equivalent Circuit

The value of the current source is obtained by placing a short across terminals A - B and measuring the short circuit current (I_{SC}) that flows. The parallel resistance is the same resistance that was determined for Thevenins equivalent circuit. As an example, let us consider the same circuit which was analyzed by Thevenin's theorem.

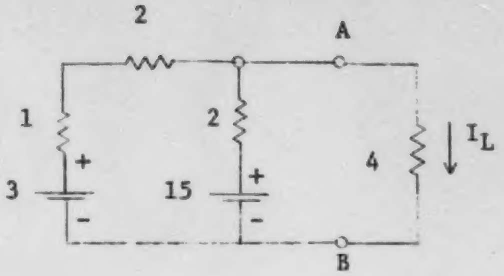


Figure 2

The first step in our procedure is to determine the short circuit current (I_{SC}) which flows after we short terminals A - B. This is illustrated in Figure 3.

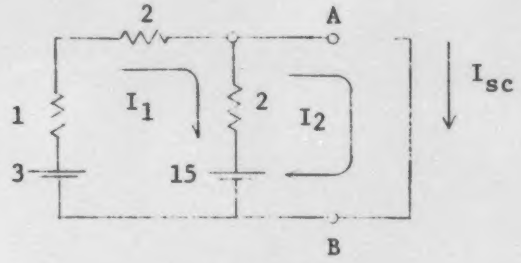


Figure 3 - Circuit to Determine I_{SC}

Writing the two loop equations yields

$$(3 - 15) = I_1 (5) - I_2 (2) \qquad (1)$$

$$(15) = - I_1 (2) + I_2 (2) \qquad (2)$$

$$-12 = 5I_1 - 2I_2 \qquad (1)$$

$$15 = -2I_1 + 2I_2 \qquad (2)$$

Solving for I_2 by determinants

$$I_2 = \frac{\begin{matrix} 5 & -12 \\ -2 & 15 \end{matrix}}{\begin{matrix} 5 & -2 \\ -2 & 2 \end{matrix}} = \frac{-15 \ -24}{10 \ -4} = \frac{51}{6} = \frac{17}{2}$$

Therefore

$$I_{SC} = I_2 = \frac{17}{2}$$

To determine the Norton resistance, we set the voltage sources to zero. The circuit then results in

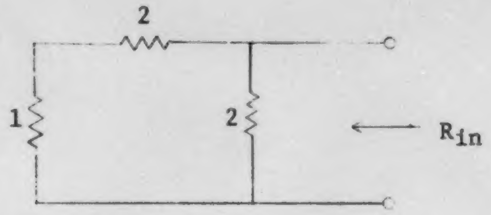


Figure 4

Solving for R_N yields, as before

$$R_N = \frac{3\ (2)}{3 + 2} = \frac{6}{5}$$

This results in the Norton equivalent circuit shown in Figure 5.

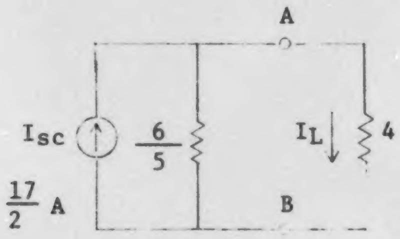
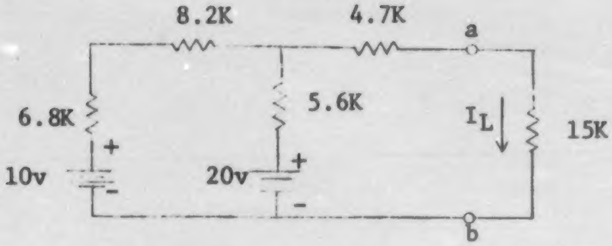


Figure 5

Now applying the current divider expression results in

$$I_L = \frac{\frac{6}{5}}{\frac{6}{5} + 4} \times \frac{17}{2} = 1.96 \quad \text{as before}$$

Laboratory Operation Procedure:



1. Determine I_L by applying Norton's Theorem.

2. Construct the circuit and measure I_L.

3. Short the 15K resistor and measure I_{SC}.

4. Open the circuit at points A and B and measure the voltage E_{OC}.

5. The Thevenin resistance is equal to

$$R_N = \frac{E_{OC}}{I_{SC}}$$

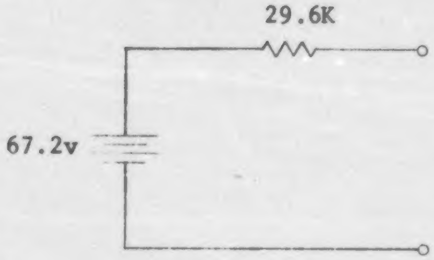
6. Construct the Norton equivalent circuit and measure I_L.

Note, that in order to construct the Norton equivalent circuit, we need a constant current generator. We can build one if we place in series with a voltage source a very large resistor compared to the other resistors in the circuit. In this case the current drawn is not dependent on the rest on the circuit.

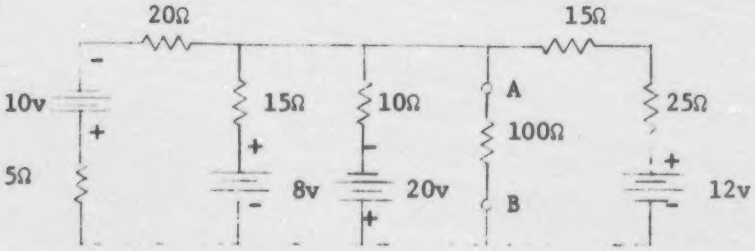
Norton's Theorem

Preparation Test:

1. Change the following Thevenin's Equivalent Circuit to a Norton's Equivalent Circuit.



2. Find the Norton's Equivalent Circuit for the circuit shown below.

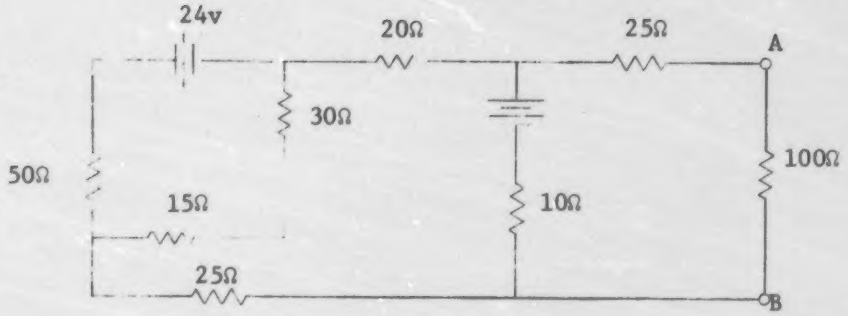

20Ω
15Ω
10v
-
+
5Ω
15Ω
+
-
8v
10Ω
-
+
20v
A
100Ω
B
25Ω
+
-
12v

Phase 11 **Norton's Theorem**

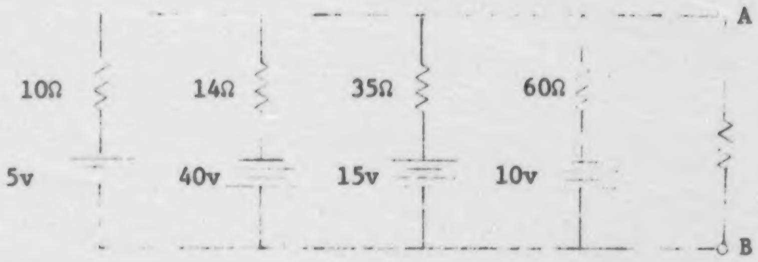
Homework Exercises:

Find the Norton's Equivalent Circuit for the following circuits.

1.


24v
20Ω
25Ω
A
30Ω
100Ω
50Ω
15Ω
10Ω
25Ω
B

2.


A
10Ω
14Ω
35Ω
60Ω
5v
40v
15v
10v
B

Concluding Discussion:

As seen Norton's theorem simplifies a complex network into a simple circuit. The simple circuit can then be readily analyzed. In general the parameter being sought usually dictates which theorem (Thevenin's or Norton's) gives the quickest results.

Phase 12 **Superposition Theorem**

Facts and principles to be learned from this phase.

1. Application of Superposition theorem.

Preliminary Discussion:

It is possible to solve a network which contains more than one source of EMF by applying the superposition theorem. When applying this theorem to a network it is possible to avoid the simultaneous solution of Kirchoff's laws.

Discussion:

The superposition theorem states that the current in any branch of a network is the algebraic sum of the currents separately produced by each source of EMF.

If a network has more than one source of EMF, the branch currents may be determined by considering one source of EMF at a time. The sources of EMF that are not being considered are shorted and replaced by their internal resistance. Let us consider the same example as before. The circuit is repeated in Figure 1.

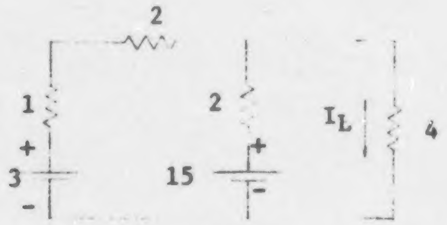


Figure 1

Once again it is desired to determine the current I_L.

Our first step is to set the 15 volt source to zero. This results in Figure 2.

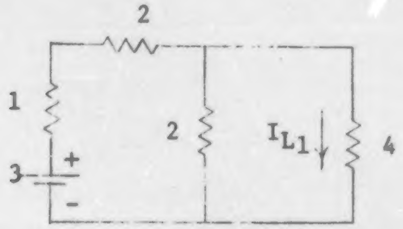


Figure 2

We will now solve for the current which flows due to the three volt source. The parallel combination of the two and four ohm resistor is,

$$Rp = \frac{2 \times 4}{2 + 4} = \frac{8}{6} = 1.33 \text{ ohms.}$$

The loop current is,

$$I = \frac{3}{1 + 2 + 1.33} = \frac{3}{4.33} = 0.693 \text{ amps.}$$

The voltage drop across the parallel combination is,

$$V_P = 0.693\ (1.33) = 0.924 \text{ volts}$$

Therefore the current through the 4 ohm resistor is

$$I_{L1} = \frac{V_P}{4} = \frac{0.924}{4} = 0.23 \text{ amps.}$$

In a similar manner now, we set the 3 volt source to zero and again solve for the current through the 4 ohm resistor due to the 15 volt source. This results in Figure 3.

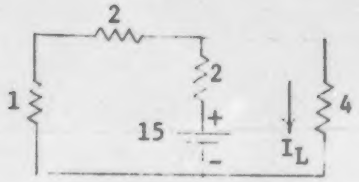


Figure 3 - Setting the 3 Volt Source to Zero

The circuit in Figure 3 can be simplified to the circuit shown in Figure 4.

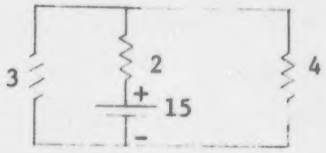


Figure 4

We can combine the 3 and 4 ohm resistor since they are in parallel.

$$R_P = \frac{3 \times 4}{3 + 4} = \frac{12}{7} = 1.72 \text{ ohms}$$

Combining these two results in the circuit shown below.

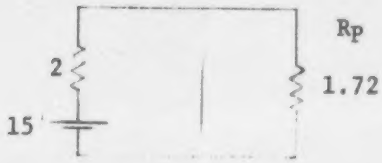


Figure 5

The circuit current is therefore

$$I = \frac{15}{2 + 1.72} = 4.03$$

The voltage drop across the parallel combination is

$$V_P = 4.03\ (1.72) = 6.9 \text{ volts.}$$

Therefore the current through the 4 ohm resistor is

$$I_{L_2} = \frac{6.9}{4} = 1.73 \text{ amps.}$$

The total current through the 4 ohm resistor is now,

$$I_L = 1.73 + .23 = 1.96$$

Thus we have solved for the circuit of Figure 1 by three different methods, Thevenin's, Nortons and the Superposition Theorem. Usually one of the theorems may simplify the circuit more than the others. With experience one can tell which theorem simplifies the network more than the others.

Laboratory Operation Procedure:

1. For each of the circuits below, determine by the Superposition Theorem I_K.
2. Construct each circuit and measure I_K. Compare with the value determined in step 1.

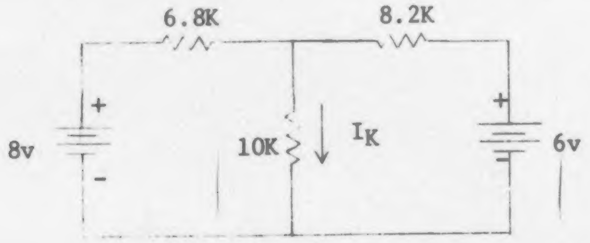


Figure (a)

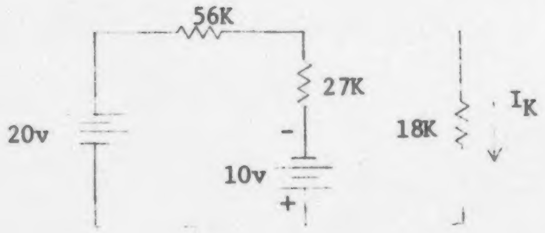
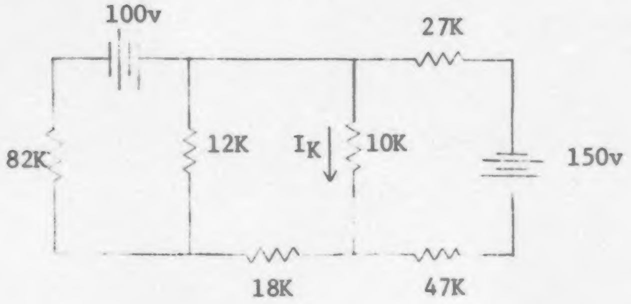


Figure (b)

Preparation Test:

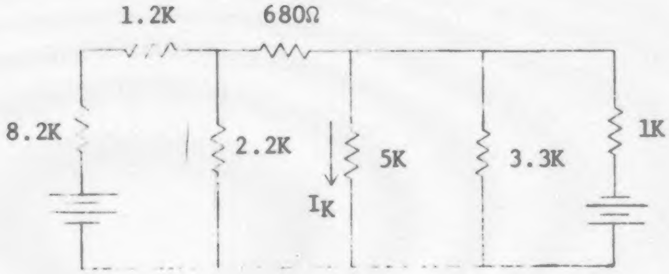
Solve for I_K in the following circuits by Superposition.

1.


100v
27K
82K
12K
I_K
10K
150v
18K
47K

Assume two different battery voltages for problem 2.

2.


1.2K
680Ω
8.2K
2.2K
I_K
5K
3.3K
1K

Superposition Theorem

Homework Exercises:

Solve for I_K in each of the following circuits by use of the Superposition Theorem.

1.

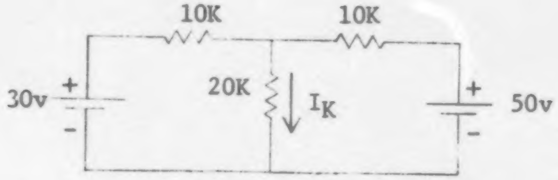
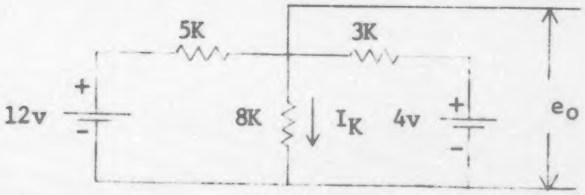

10K
10K
30v
+
-
20K
I_K
+
-
50v

Figure (a)

2.


5K
3K
12v
+
-
8K
I_K
4v
+
-
e_o

Solve for e_o also

Figure (b)

Concluding Discussion:

When applying the Superposition theorem, it is essential that the internal resistance of every power supply be included. Thevenin's, Norton's and the Superposition theorem will be applied in the final phase of this problem.

Phase 13 Voltage Dividers

Facts and principles to be learned from this phase.

1. Characteristics and application of a voltage divider.

Preliminary Discussion:

In partically all electronic systems various voltages are usually required at different point in the system. The most practical method of obtaining these various voltages is with the use of a voltage divider network.

A simple voltage divider network consists of two resistors in series. As an introductory example let us analyze the simple voltage divider shown in Figure 1.

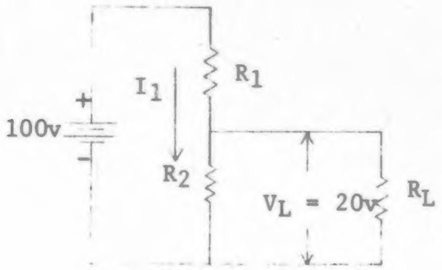


Figure 1 - Simple Voltage Divider

Suppose a 100 volt supply is available and it is required to have 20 volts across a load R_L. For the simple case, we will assume that R_L is verv large compared to R_2 so that it does not load down the voltage divider, i.e., assume that R_L draws negligible current. The current flowing through R_1 and R_2 is called the bleeder current. In general, the bleeder current should be approximately 10% of the total current supplied.

Writing Kirchoff's voltage law equation around the loop, gives

$$100 = I_1R_1 + I_1R_2$$

Solving for the current I_1 yields,

$$I_1 = \frac{100}{R_1 + R_2} \qquad (1)$$

The voltage V_L is,

$$V_L = I_1R_2 = \frac{100\ R_2}{R_1 + R_2} \qquad (2)$$

and since it is desired to have $V_L = 20$ volts.

$$20 = \frac{100\ R_2}{R_1 + R_2}$$

$$\frac{1}{5} = \frac{R_2}{R_1 + R_2}$$

Solving for R_1 yields,

$$R_1 = 4R_2$$

Therefore making R_1 four times greater than R_2 and also with the requirement that $R_L >> R_2$ results in the desired 20 volts across R_L.

In the previous example the design of the voltage divider was simplified since we assumed no load effect. In a practical application this loading effect (the current drawn by the load R_L) cannot be neglected. Let us now consider the case where the load draws appreciable current. Suppose a 200 volt supply is available and it is desired to supply a load with 15 ma at 150 volts.

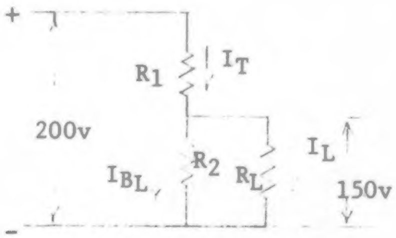


Figure 2

Applying the general rule that the bleeder current should be approximately 10% of the total current results in a bleeder current of 1.5 ma.

Therefore the total current supplied is the load current plus the bleeder current or 15 + 1.5 = 16.5 ma.

Solving for the required value of R_2 and R_1 yields,

$$R_2 = \frac{150\ \text{v}}{1.5\ \text{ma}} = 100\text{K}$$

$$R_1 = \frac{200 - 150}{16.5\ \text{ma}} = \frac{50}{16.5\ \text{ma}} = 3.03\text{K}$$

The load resistance can also be calculated as,

$$R_L = \frac{150\ \text{v}}{15\ \text{ma}} = 10\text{K}$$

Laboratory Operation Procedure:

1. Design a voltage divider to meet the following specifications.

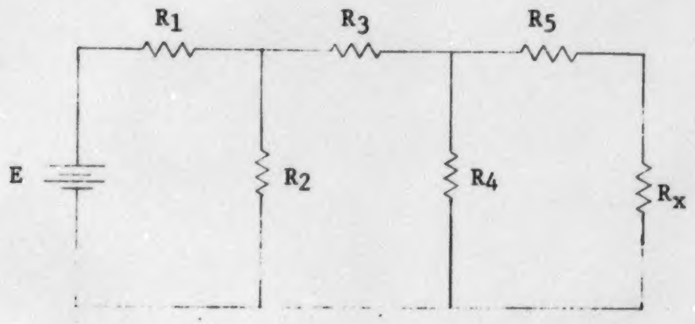
Supply Voltage		60 v		
Load	R_{L1}	30 v	@	8 ma
Load	R_{L2}	45 v	@	2 ma
Load	R_{L3}	60 v	@	5 ma

2. Obtain the resistors with values as close to the design values as possible and construct the circuit. Check to see that the desired currents and voltages are obtained.

Preparation Test:

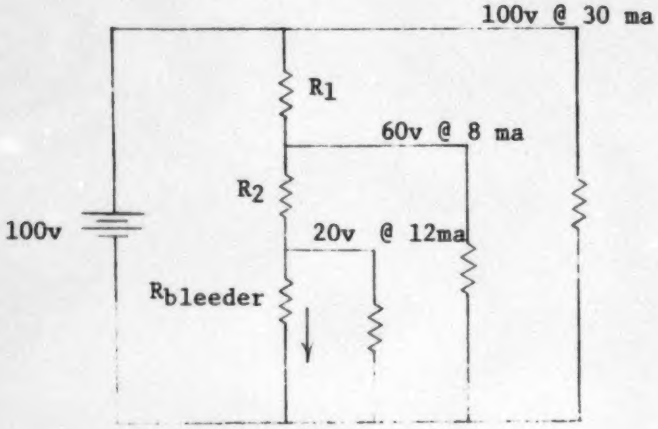
1. Design a voltage divider to supply the following loads from a 200 volt power supply. 150 v @ 25 ma, 100 v @ 10 ma, 75 v @ 1 ma, and 25 v @ 20 ma.

2. Derive an expression for the voltage across R_x in the following circuit?

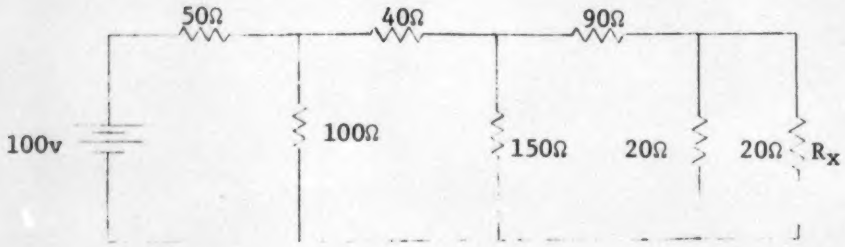


Homework Exercises:

1. What value of bleeder resistance should be used in the following voltage divider if the bleeder current is 5 ma?


100v @ 30 ma
R1
60v @ 8 ma
R2
100v
20v @ 12ma
Rbleeder

2. What is the voltage across R_x in the following circuit?


50Ω
40Ω
90Ω
100v
100Ω
150Ω
20Ω
20Ω
Rx

Concluding Discussion:

Use of the voltage divider is a very useful tool. It can save time when analyzing a given circuit. A circuit which divides current, a current divider will now be analyzed.

Phase 14 Current Divider

Facts and principles to be learned from this phase.

1. Basic action of a current divider

Preliminary Discussion:

A current divider is basically a network which reduces an input current. Consider the circuit in Figure 1.

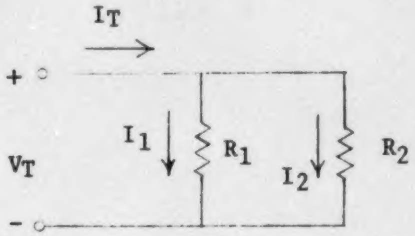


Figure 1 - Simple Current Divider

Figure 1 is a simple parallel network being supplied with a current I_T. It is desired to obtain the current I_1 and I_2. The voltage across this parallel combination is given by the following expression.

$$V_T = I_T \frac{R_1 R_2}{R_1 + R_2} \qquad (1)$$

The current I_1 is then,

$$I_1 = \frac{V_T}{R_1} = \frac{I_T \dfrac{R_1 R_2}{R_1 + R_2}}{R_1} \qquad (2)$$

$$I_1 = I_T \frac{R_2}{R_1 + R_2}$$

The current through the resistor R_2 is,

$$I_2 = \frac{V_T}{R_2} = I_T \frac{R1}{R_1 + R_2} \qquad (3)$$

We therefore can conclude that when a current splits between two resistors the current through one resistor is directly proportional to the other resistor and inversely proportional to the sum of the two resistors. As a practical example, let us consider the circuit in Figure 2.

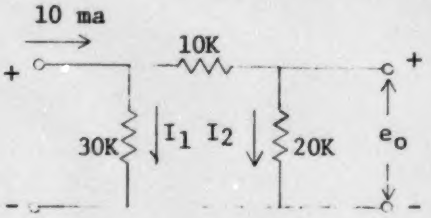


Figure 2

It is desired to determine the output voltage E_o. This problem can easily be solved once I_2 is determined. Using the current divider expression,

$$I_2 = 10 \times \frac{30K}{30K + 10K + 20K} = 10 \times \frac{30}{60} = 5 \text{ ma}$$

Therefore the output voltage E_o is

$$E_o = I_2 \text{ (20K)} = 5 \times 20 = 100 \text{ volts}$$

As seen, the output voltage is readily computed by applying the current divider expression.

Laboratory Operation Procedure:

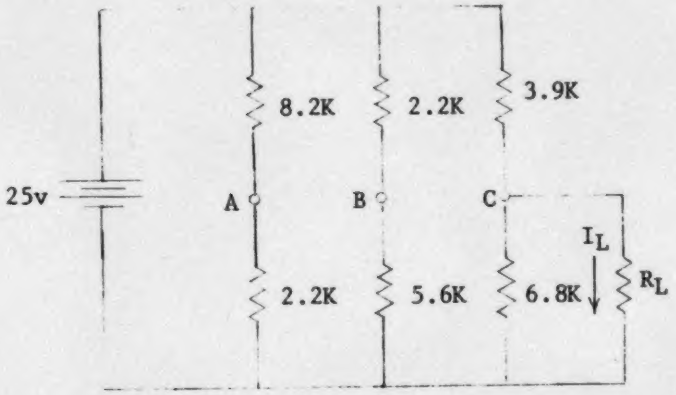
1. Measure and record the resistances that are to be used in the circuit below.

2. Determine the value of R_L which will allow 1 ma to flow through it.

3. Set up circuit and measure the current through R_L.

4. Using the value of R_L from step 2, determine the current through it if points A, B, and C are connected together.

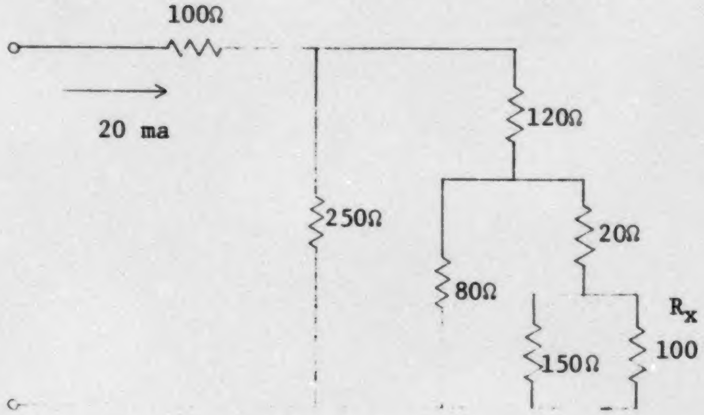
5. Set up the circuit and measure the current through R_L.


25v
8.2K
2.2K
3.9K
A
B
C
I_L
2.2K
5.6K
6.8K
R_L

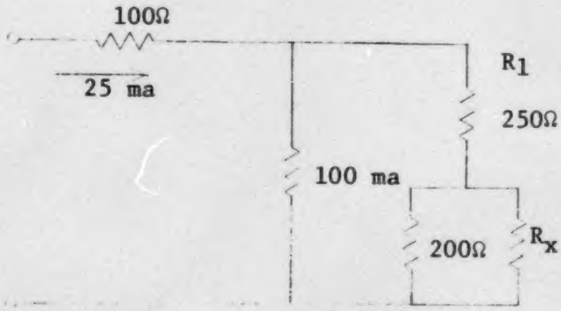
Phase 14 **Current Divider**

Preparation Test:

1. Find the current through R_x in the following circuit.

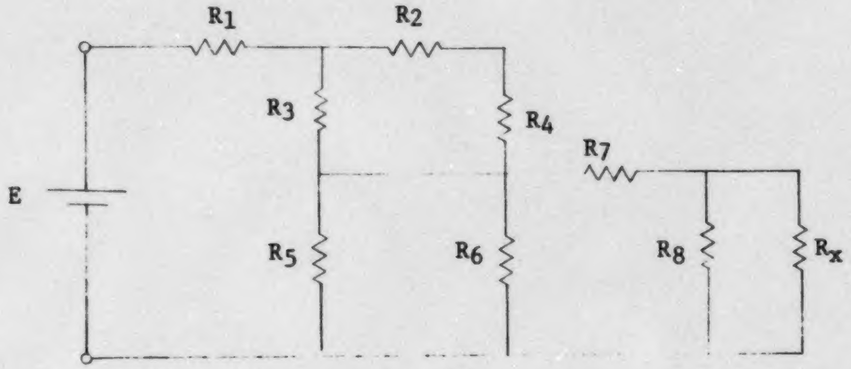

100Ω
20 ma
120Ω
250Ω
20Ω
80Ω
R_x
100
150Ω

2. What value of R_x will allow 5 ma to flow through R_1?

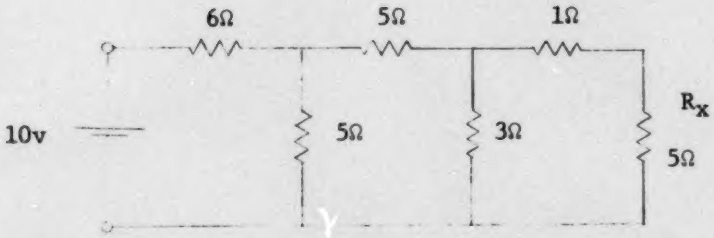

100Ω
25 ma
R_1
250Ω
100 ma
200Ω
R_x

Homework Exercises:

1. Derive an expression for the current through R_x in the following circuit


R_1
R_2
R_3
R_4
R_7
E
R_5
R_6
R_8
R_x

2. What current will flow through R_x in the following circuit?


6Ω
5Ω
1Ω
R_x
10v
5Ω
3Ω
5Ω

Concluding Discussion:

The current divider expression is very helpful when analyzing many circuits. In many cases it can save valuable time.

Ammeters

Facts and principles to be learned in this phase.

1. Construction of basic D'Arsonval meter.
2. Design of a meter to increase the maximum current capability of a basic meter movement.

Preliminary Discussion:

Since the primary function of a technician is testing and troubleshooting circuits with the aid of meters, it is important that he have a basic understanding of these meters. All d-c meters work on the principle that the needle (pointer) deflection is proportional to the current which is being measured. The most common type of meter in use today is the permanent magnet moving coil system, commonly referred to as the D'Arsonval movement.

Discussion:

The D'Arsonval meter movement works on the principle of two magnetic fields interacting with each other. When a magnet which is free to rotate is placed in the vicinity of a fixed magnet, there will be a force exerted on the movable magnet such that unlike poles align opposite one another. Let us first consider the electromagnet shown in Figure 1.

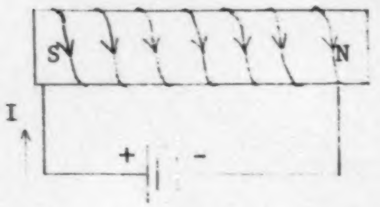


Figure 1 - Simple Electromagnet

With the battery connected as shown conventional current flows as indicated. Use of the right hand rule enables us to determine that the magnetic lines of flux emerge from the right end and enter the left end of the bar, thus creating an electromagnet with poles as indicated. Placing this electromagnet inside a magnetic field and adding a spring forms the basic D'Arsonval meter. This is illustrated in Figure 2.

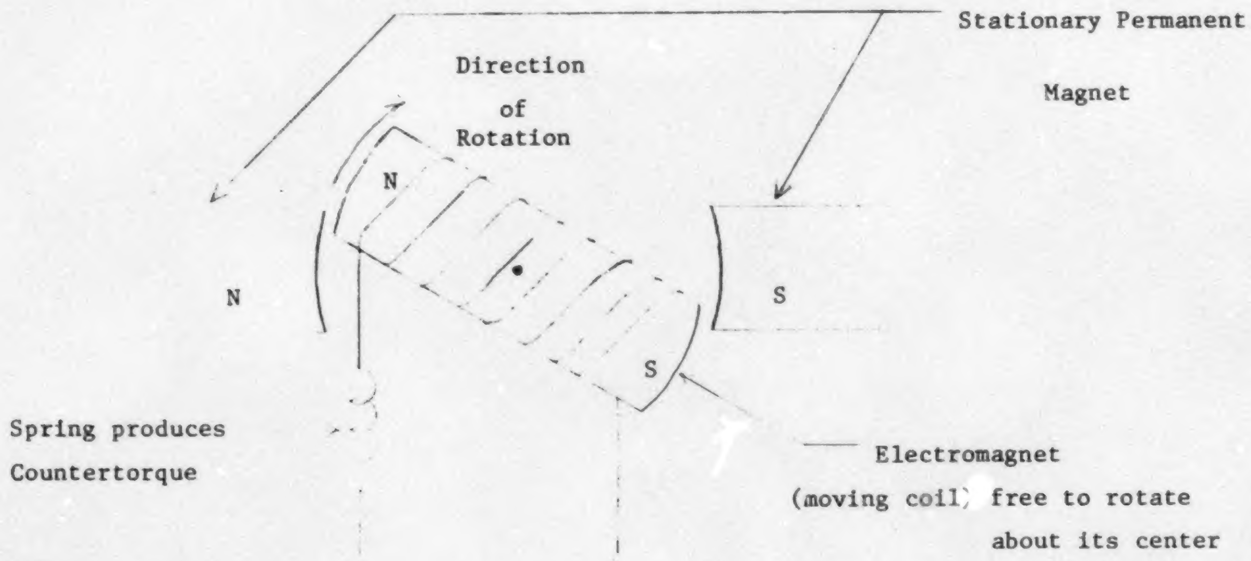

Stationary Permanent
Magnet
Direction
of
Rotation
N
N
S
S
Spring produces
Countertorque
Electromagnet
(moving coil) free to rotate
about its center

Figure 2 - Basic D'Arsonval Meter Movement

Let us analyze the action of this moving coil system. The current to be measured is applied to the moving coil as shown. The moving coil attains poles as indicated which interacts with the magnetic field of the permanent magnet. The spring supplies the torque to oppose the torque produced by the interaction of the magnetic fields. If the permanent magnet provides a flux ϕ_P and the current in the moving coil produces a flux ϕ_C, the turning torque on the moving coil is proportional to the product of the two fluxes. This is expressed as

$$T = k \phi_C \phi_P \qquad (1)$$

where k is a proportionality constant. Since ϕ_P is a constant, we can rewrite equation (1) as,

$$T = k_1 \phi_C \qquad (2)$$

where $k_1 = k \phi_P$

now since ϕ_C is directly proportional to the current in the coil, we can say

$$\phi_C = k_2 I \qquad (3)$$

where I is the current in the coil and k_2 is a proportionality constant. Therefore

$$T = k_3 I \qquad (4)$$

Thus the torque and therefore the angle of rotation on the moving coil is directly proportional to the current in the coil.

In order to complete the basic D'Arsonval meter, we need to add a needle to the moving coil and a scale to indicate the value of current being measured. The complete basic D'Arsonval meter is shown in Figure 3.

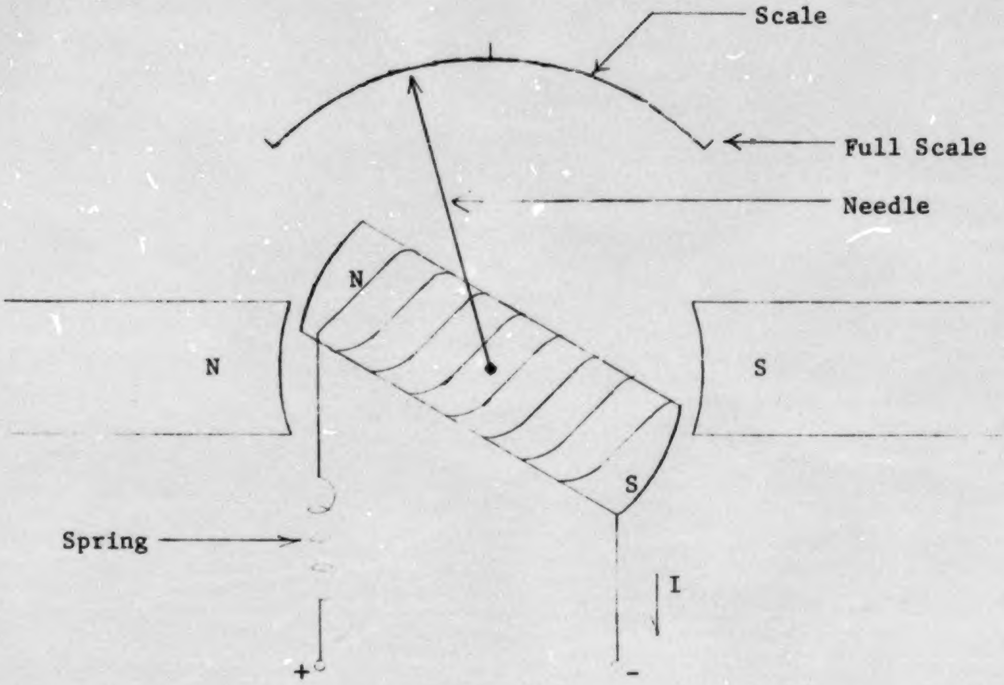


Figure 3 - Basic D'Arsonval Meter

The basic meter movement is designed so that when a certain amount of current flows through the moving coil, the needle deflects to the full-scale position. The current required to produce this full-scale deflection is called the meter's deflection sensitivity. For example, a meter which requires 1 ma for full-scale deflection has a deflection sensitivity of 1 ma.

The moving coil is constructed by winding turns of copper wire around a soft iron bar. The coil being made from copper has a certain amount of resistance. Since the current to be measured flows through this coil, every meter has a certain amount of resistance associated with it. Thus we can model the basic meter movement with the coil resistance R_M, in series with an ideal meter having no resistance. This is shown in Figure 4.

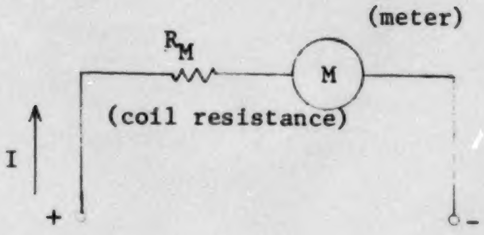


Figure 4 - Model for Basic Meter Movement

The maximum current of a meter may be increased by adding a resistor in parallel with the basic meter. Suppose we have a 100 ohm basic movement with a deflection sensitivity of 1 ma, and we wish to increase the capability of the meter so that it can read up to 3 ma. We must therefore shunt the basic movement of a suitable resistor. A circuit diagram is shown in Figure 5.

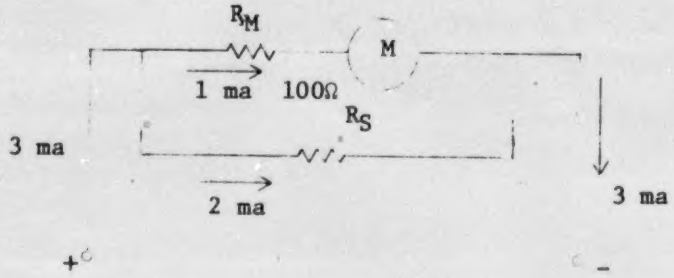


Figure 5

The calculation of the shunt resistor is as follows: Since the basic movement is only capable of handling 1 ma, we must bypass 2 ma through the shunt resistor. We now have a parallel circuit which has to be analyzed. This is shown in Figure 5. The voltage across the parallel circuit is

$$V = I_M R_M = 1\ (.1) = 0.1 \text{ volts}$$

The total current is equal to the meter current I_M, plus the shunt current I_S.

$$I_T = I_M + I_S$$

Solving for the shunt current I_S, yields

$$I_S = I_T - I_M = 3 - 1 = 2 \text{ ma.}$$

Therefore the value of the shunt resistor is

$$R_S = \frac{V}{I_S} = \frac{0.1\text{v}}{2 \text{ ma}} = 50 \text{ ohms.}$$

The value of R_S can easily be computed by the following expression. We can say that,

$$I_M R_M = I_S R_S$$

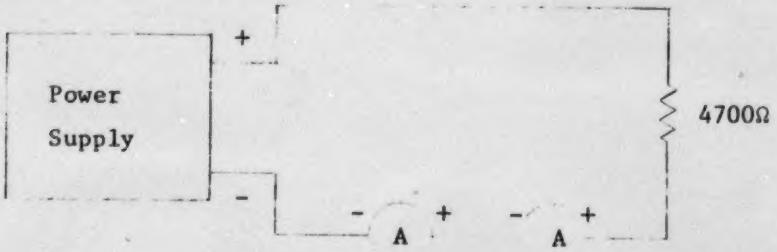
solving for R_S yields

$$R_S = \frac{I_M}{I_S} R_M = \frac{1}{2} (100) = 50 \text{ ohm.}$$

Therefore by placing a 50 ohm resistor in shunt with the basic meter, we have increased the meters capability from 1 ma to 3 ma.

Laboratory Operation Procedure:

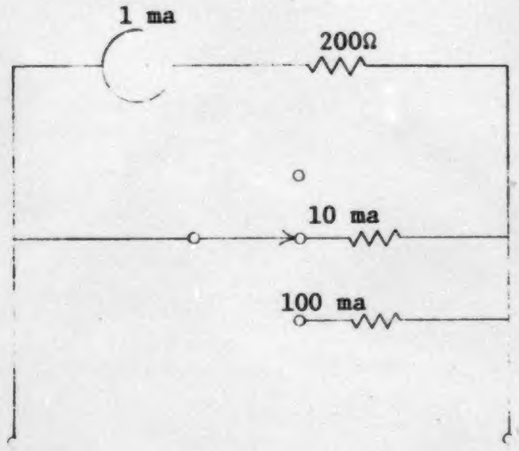
1. A 0-10 milliampere instrument is to be constructed. Using the resistance shown on the basic meter movement, compute the necessary shunt resistor and its power dissipation .
2. Obtain the proper resistor and construct the meter.
3. Check the resultant instrument calibration against a Student meter (the latter switched to its 10 ma range). Use the calibration circuit below.



Preparation Test:

1. Design an ammeter to read 1 amp at full-scale with a 5 ma movement having a resistance of 100 ohms.

2. Solve for the shunt resistors in the following ammeter so that it has a 1 ma, 10 ma, and 100 ma range. It uses a 1 ma movement with a resistance of 200 ohms.



Homework Exercises:

1. A 100 ohm movement with a deflection sensitivity of 1 ma is shunted such that it can measure 5 ma full-scale. What is the value of the shunt resistor?

2. A multiscale ammeter has scales of 1 ma; 5 ma; 10 ma; 20 ma. A 100-µa movement with 50 ohms of resistance is used. Calculate the values of the four shunt resistors.

Concluding Discussion:

The important point to remember when designing an ammeter from a basic meter movement is that the current through the moving coil cannot exceed the current required for full-scale deflection. It also should be easy to see that the basic meter movement can be extended to a multirange meter by adding several internal shunts.

Phase 16 Voltmeters

Facts and principles to be learned in this phase.

1. Construction of a voltmeter.
2. Increasing the voltage range of a basic meter movement.
3. Concept of voltmeter sensitivity.

Preliminary Discussion:

Suppose a 1 ma movement which has a coil resistance of 100 ohms is available. At full-scale the current flowing through the meter is 1 ma and the voltage across the meter is, from ohm's law,

$$V_M = I_M R_M = (1 \text{ ma})\ (100\Omega) = 0.1\text{v} = 100 \text{ mv}.$$

If the same movement has 0.5 ma flowing through it, the voltage across the terminals is,

$$V_M = I_M R_M = (.5 \text{ ma})\ (100 \text{ ohm}) = 50 \text{ mv}.$$

Therefore not only does the meter measure current, but it measures voltage as well. Thus this meter could also be calibrated in millivolts. The voltage range of the meter can be increased by placing a resistor in series with the basic meter movement. Suppose, for example, we wish to increase the voltage range of the basic meter movement so that it is able to measure up to 5 volts full-scale. The procedure for calculating the value of the series resistor (R_X) is as follows:

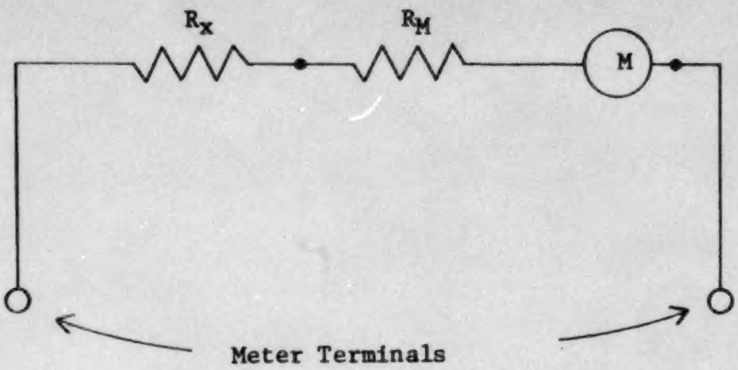


Figure 1 - Circuit for Increasing the Voltage Range of a Basic Meter Movement

The basic meter movement gives full-scale deflection at 1 ma.

Since it is desired to read up to 5 volts, the voltage across the terminals of the meter should be 5 volts when 1 ma is flowing through the meter. Therefore the series combination of R_X and R_M is

$$R_X + R_M = \frac{E}{I_M} = \frac{5\text{ v}}{1\text{ ma}} = 5K$$

$$R_X = 5000 - R_M = 5,000 - 100 = 4900 \text{ ohms.}$$

Therefore by adding a 4,900 ohm resistor in series with the basic meter movement, we increase the range of the meter so that we can read 5 volts full-scale. The total resistance on the 5 volt range is 5,000 ohms. The total resistance divided by the full-scale deflection voltage gives the voltmeter sensitivity. For the voltmeter described above, the sensitivity is,

$$\frac{5,000 \text{ ohms}}{5 \text{ volts}} = 1,000 \text{ ohms per volt}$$

Note that this figure is unchanged by adding R_X. It is a basic property of a meter and does not change for different values of R_X.

For example if we wish to construct a meter to read 20 volts full-scale, using the same basic meter movement, we require $R_X + R_M$ to equal,

$$R_X + R_M = \frac{E}{I_M} = \frac{20}{1\text{ ma}} = 20,000 \text{ ohms.}$$

Thus the voltmeter's sensitivity is,

$$\frac{20{,}000 \text{ ohms}}{20 \text{ volts}} = 1{,}000 \text{ ohms per volt},$$

the same as before.

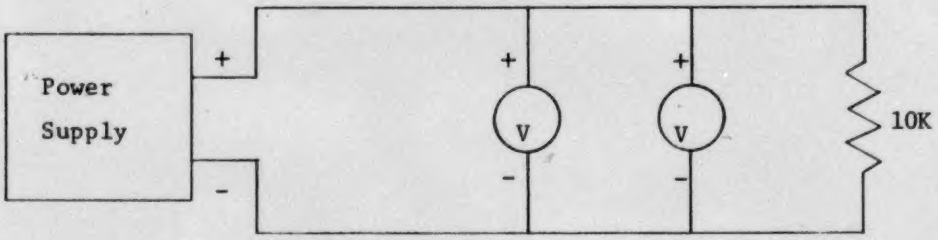
We can also determine the voltmeter's sensitivity by taking the reciprocal of the current sensitivity of a meter. For the meter above this results in

$$\frac{1}{1 \text{ ma}} = 1{,}000 \text{ ohms per volt},$$

which is the same as before.

Laboratory Operation Procedure:

1. Using the 1 ma basic meter movement design and construct a 0-100 volt instrument having a sensitivity of 1,000 ohms per volt. Compute the necessary series resistor.
2. Using the circuit below, check the calibration against a student meter. Place the student meter's switch on the 100 volt range.



3. Design and construct a 0-100 volt meter having a sensitivity of 100 ohms per volt.

   Repeat step 2 for this meter.

Voltmeters

Preparation Test:

1. Design a 0-100 volt voltmeter with a sensitivity of 1,000 ohms per volt using a 1 ma movement with a resistance of 250 ohms.

2. Design a voltmeter to read 150 volts full-scale with a sensitivity of 100 ohms per volt using a 100 μa movement with a resistance of 300 ohms.

Homework Exercises:

1. A meter movement has a resistance of 50 ohms and a full-scale deflection of 1 ma. What is the value of the resistor required to increase the meter range so that it is able to read up to 200 volts full-scale?

2. A 50 μa movement whose total resistance is 1,000 ohms is used to construct a voltmeter. Calculate the series resistors required for 30v and 150 volt ranges.

Concluding Discussion:

Ammeters and voltmeters are constructed from the same basic meter movement. The difference lies in the method in which the external resistance is connected. The ammeter has the external resistance connected in parallel with the moving coil while the voltmeter has the external resistor in series with the moving coil.

Good ammeters should offer a very small resistance while a good voltmeter should offer a fairly large resistance.

Phase 17 Loading Effect of Voltmeters

Facts and principles to be learned in this phase.

1. Effect of different voltmeters in a circuit.

Preliminary Discussion:

An ideal voltmeter should draw no current, but since the moving coil requires a small current to obtain a reading, the voltmeter must draw this current from the circuit which is being measured. Therefore in order to obtain accurate readings the voltmeter should not load down the circuit appreciably. The voltmeter should thus have a high resistance if the above is to be true. Let us consider the circuit of Figure 1.

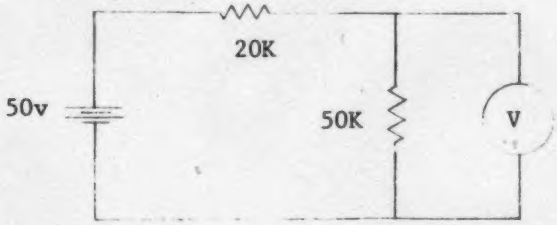


Figure 1 - Circuit to Demonstrate the Effect of Different Voltmeter Sensitivities

Theoretically the voltage drop across the 50 K resistor is by the voltage divider expression,

$$V_{50K} = \frac{50}{20 + 50} \times 50 = 35.7 \text{ volts}$$

Suppose we connect a 10,000 ohm per volt meter on a 50 volt full-scale across the 50 K resistor. What will this voltmeter read?

The resistance of the meter is

$$10{,}000 \frac{\text{ohms}}{\text{volt}} \times 50 \text{ volt} = 500{,}000 \text{ ohms.}$$

This 500 K resistance in parallel with a 50 K resistor results in a parallel resistance of

$$Rp = \frac{500 \times 50}{500 + 50} = 45.4 \text{ K}$$

Thus this voltmeter will read

$$V = \frac{45.4}{20 + 45.4} \times 50 = 34.7 \text{ volts}$$

or about a 3% error.

Now suppose we replace this voltmeter with one that has a sensitivity of 1,000 ohms per volt on the 50 volt scale. What will this voltmeter read? A 1,000 ohm per volt meter on a 50 volt range has a resistance of

$$R = 1{,}000 \frac{\text{ohms}}{\text{volt}} \times 50 \text{ volts} = 50{,}000 \text{ ohms.}$$

Therefore this resistance in parallel with the 50 K resistor has a parallel combination of 25 K and the voltmeter will now read

$$V = \frac{25}{20 + 25} \times 50 = 16.7 \text{ volts}$$

which represents an error of over 50%. Therefore it can be concluded that the higher the voltmeter sensitivity, the more accurate will be the voltmeter reading.

Laboratory Operation Procedure:

1. Calculate the total resistance of each voltmeter constructed in the preceding phase.

2. For the circuit below, calculate the voltage V_{AB} by five different methods, namely.

    (a) Loop Analysis

    (b) Nodal Analysis

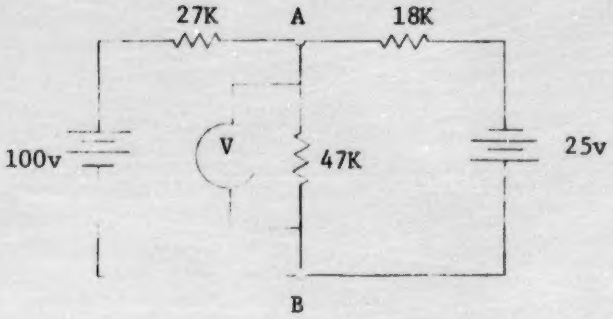
    (c) Thevenin's Theorem

    (d) Norton's Theorem

    (e) Superposition Theorem

    Include the meter resistance which was calculated in step 1.

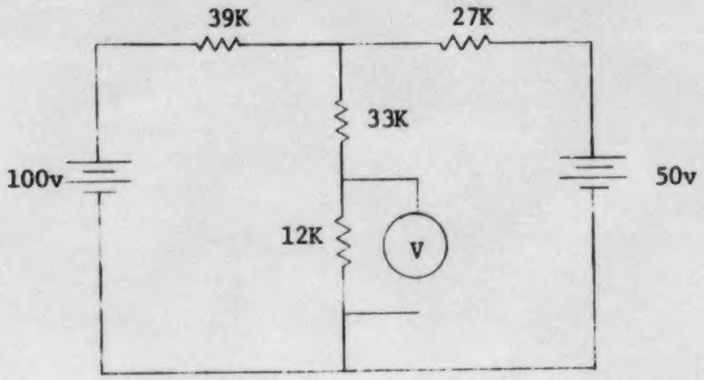
3. Construct the circuit and measure V_{AB} with each constructed voltmeter from the previous phase. Compare the results.



123

Preparation Test:

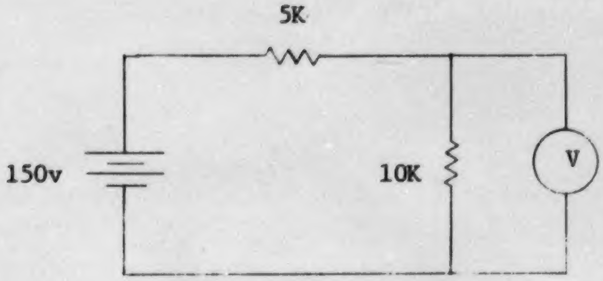
- What voltage would a 10,000 ohm per volt meter on the 0-50 volt range read if connected across the 12K resistor in the following circuit?


39K
27K
33K
100v
50v
12K
V

Loading Effect of Voltmeters

Homework Exercise:

1. (a) What would a 10 ohm per volt meter on the 0-100 volt range read if connected across the 10K resistor in the circuit below?
   (b) 100 ohm per volt on the 0-150 volt range?
   (c) 1,000 ohm per volt on the 0-250 volt range?
   (d) 10,000 ohm per volt on the 0-250 volt range?
   (e) 20,000 ohm per volt on the 0-250 volt range?



Concluding Discussion:

An ideal voltmeter should have an infinite resistance and therefore should not draw current. As discussed earlier the moving coil requires a small current to obtain a reading and therefore does offer a finite resistance. This resistance which a voltmeter introduces depends on its sensitivity. This phase should help the student in future measurements work.

PRINCIPAL PROBLEM

NUMBER 2

OSCILLOSCOPE

Statement of the Problem:

The oscilloscope is one of the most useful pieces of electronic equipment which the technician will come in contact with. The technician must be able to use the oscilloscope as a diagnostic tool. He must know its limitations and capabilities and practice its use until it becomes an extension of his senses. Learning how to establish a picture of a waveform is merely the beginning. Learning to measure and interpret the waveform for the purpose of understanding a problem is the real and most difficult part of learning how to use the oscilloscope. It is therefore imperative that the technician become very familiar with this versatile instrument. This problem is therefore designed to familiarize the student with the oscilloscope.

Phase 1

Facts and Principles to be learned in this problem.

1. Introduce the oscilloscope to the student.
2. Learn the capabilities and limitations of the oscilloscope.

Preliminary Discussion:

Basically the oscilloscope consists of a cathode - ray tube (CRT) and electronic circuits such as amplifiers, power supplies and sweep generators. The oscilloscope is a voltage indicating instrument which is generally used for observation of electrical phenomena and for making many types of measurements.

The CRT consists of three basic parts, (1) an electron gun (2) two pairs of deflection plates, and (3) a screen. The CRT is shown in Figure 1.

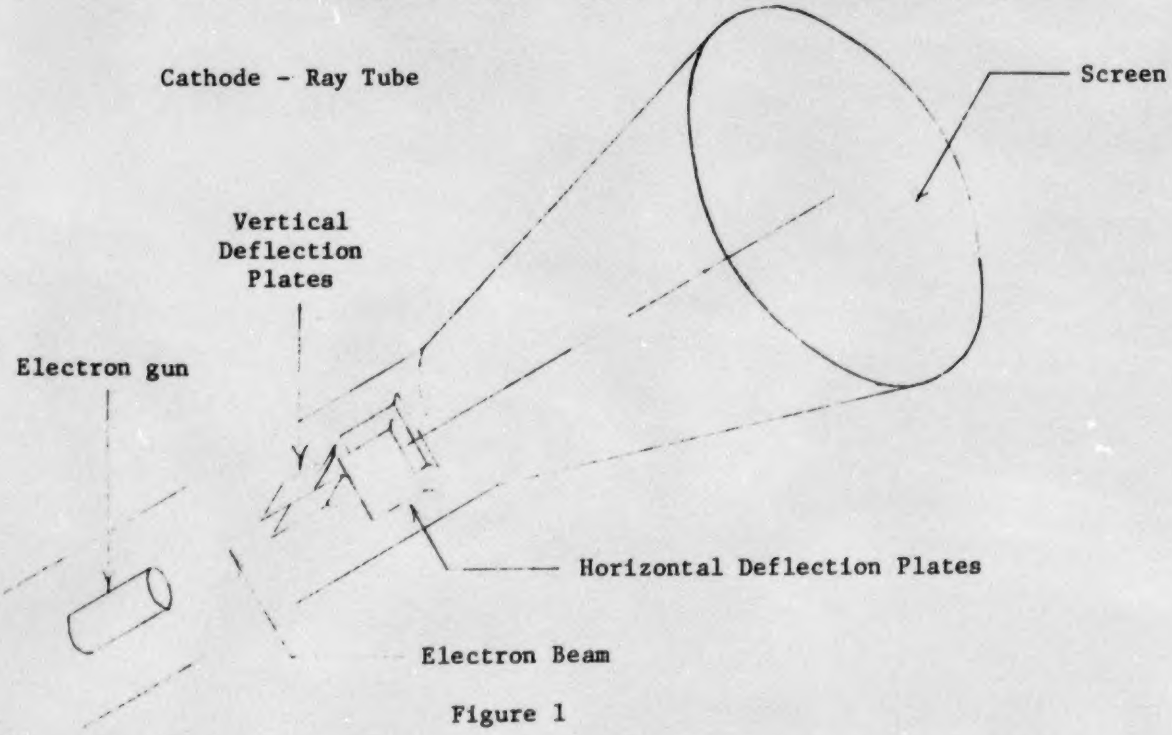

Cathode - Ray Tube
Screen
Vertical Deflection Plates
Electron gun
Horizontal Deflection Plates
Electron Beam

Figure 1

The function of the electron gun is to emit a narrow beam of high velocity electrons aimed at the screen. Upon striking the screen, the kinetic energy of the electrons is converted to light energy and a visible spot appears on the screen. The function of the deflection plates is to deflect the beam so that the visible spot will move anywhere on the screen. With no potential applied to the deflection plates; the electron beam passes through the deflection plates and strikes the center of the screen. The screen is coated with phosphor so that when the beam strikes it a visible bright spot appears. A characteristic of phospor known as phosphorescence retains the spot for a brief period. This is useful when it is desired to view a rapid change in signal level. If a d - c potential which makes the top vertical deflection plate more positive than the lower one, is applied, the electron beam will be deflected upward. The beam can be deflected downward by making the lower plate more positive than the top plate. Similarly the beam can be deflected to the right or to the left with d - c potentials on the horizontal plates. One word of caution here. The intensity of the spot should be kept as low as possible to avoid destroying the screen.

Now that we have discussed the operation of the CRT let us look at a block diagram for a typical oscilloscope. This is shown in Figure 2.

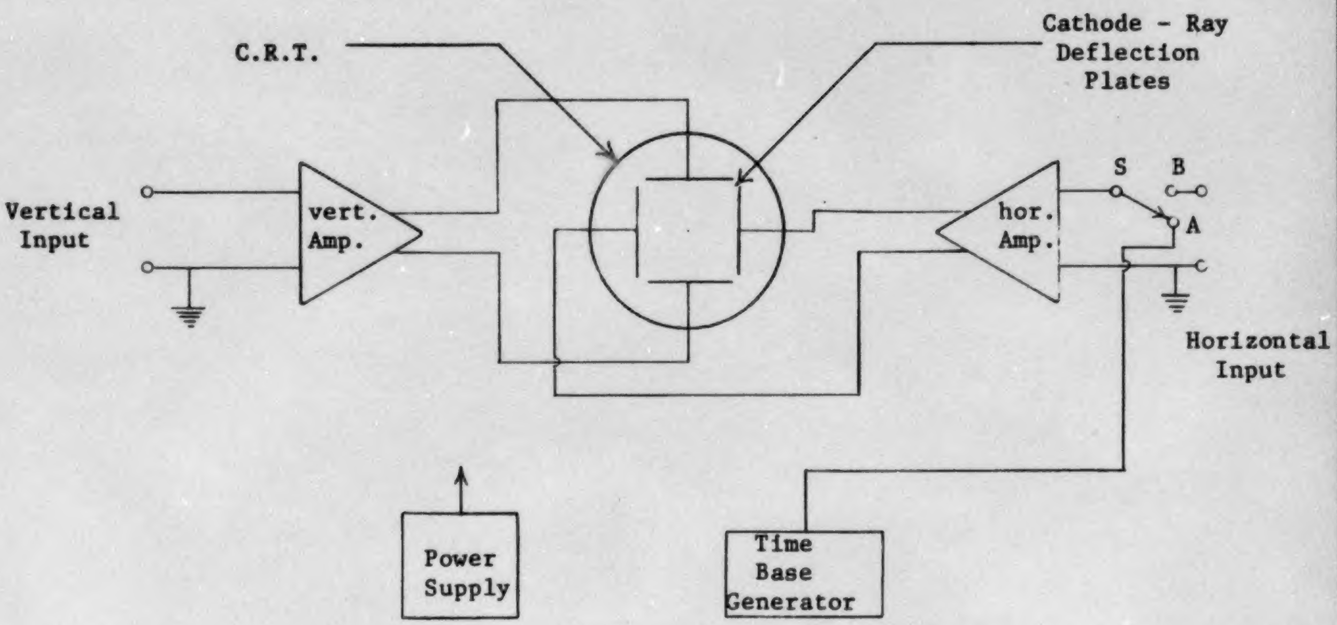

C.R.T.
Cathode - Ray Deflection Plates
Vertical Input
vert. Amp.
hor. Amp.
S
B
A
Horizontal Input
Power Supply
Time Base Generator

Figure 2 - Block Diagram of Basic Oscilloscope

Note that the basic oscilloscope consists of a;

1. Vertical amplifier
2. Horizontal amplifier
3. Time base generator
4. Power supply
5. Cathode - ray tube

When it is desired to observe a periodic time-varying waveform, switch S is placed in position A and the signal to be observed is applied to the vertical amplifier. With the switch S in this position, the time base generator provides a saw-tooth voltage which is applied to the horizontal deflecting plates through the horizontal amplifier. A typical saw-tooth wave is illustrated in Figure 3.

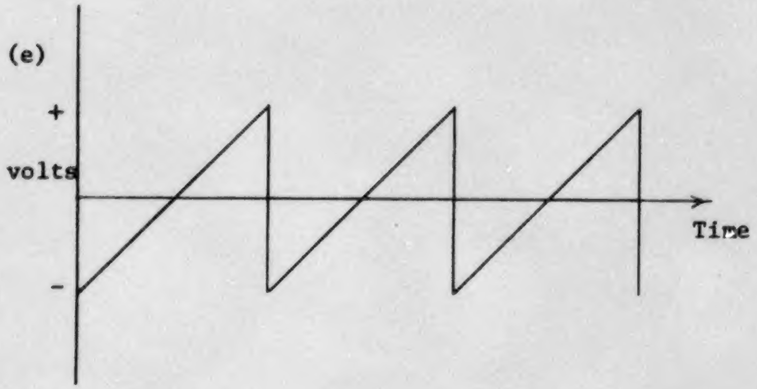
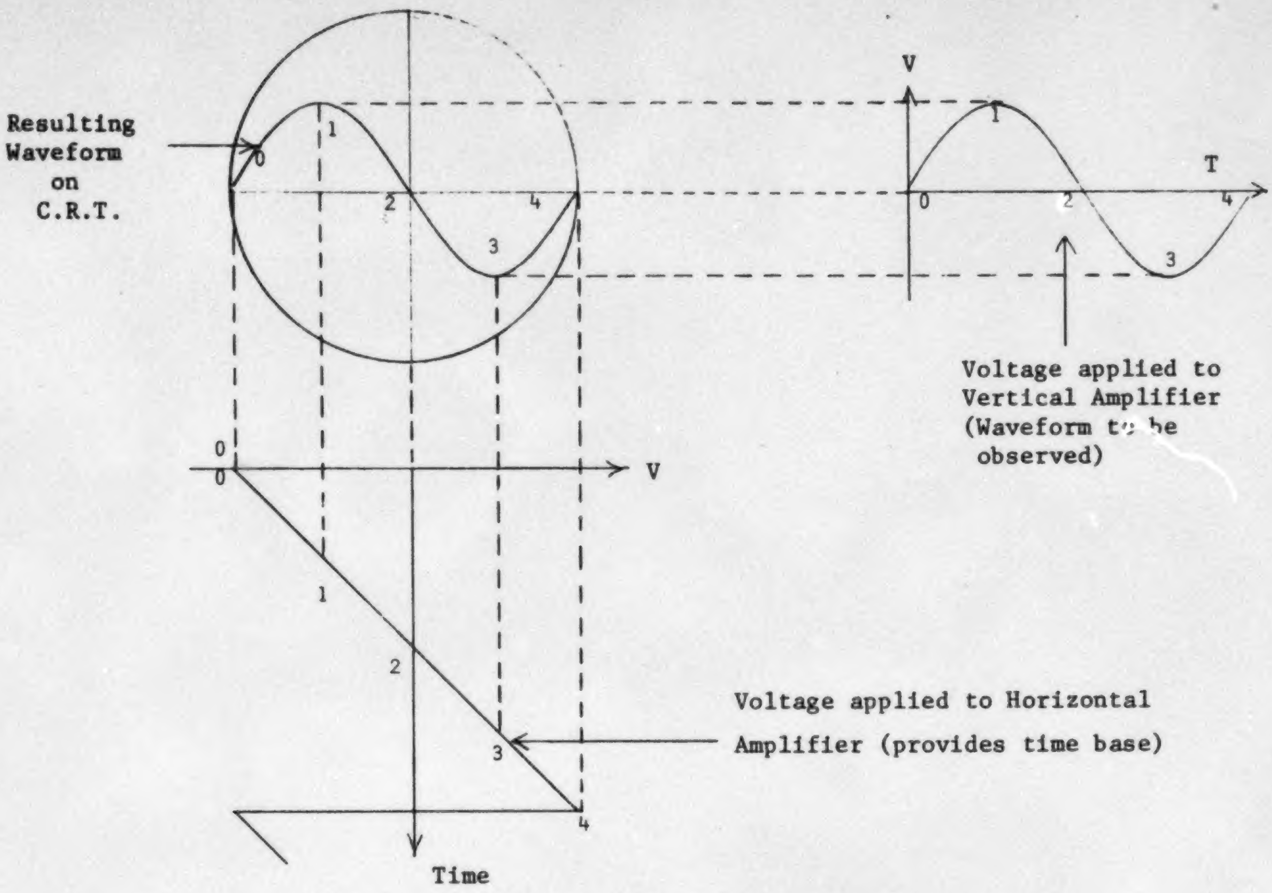


Figure 3 - Saw-tooth Signal which is Applied to the Horizontal Amplifier

As seen from Figure 3 the saw-tooth wave starts from a negative value and rises linearly to some positive maximum value. It then drops sharply to zero. When this saw-tooth wave is applied to the horizontal amplifier and with no signal applied to the vertical amplifier, the spot on the screen is deflected from left to right at a constant rate. When the saw-tooth drops back to its original negative value, the spot returns rapidly to the left then starts sweeping to the right again. This repeats at the frequency of the saw-tooth. The frequency of the saw-tooth can be varied by a selector switch which is on the face of the oscilloscope. This makes the spot travel from left to right at different rates. If the frequency of the saw-tooth is increased to a high enough value, the spot will travel from left to right at a high rate. Due to the phosphorescence of the screen, instead of seeing a spot sweep across the screen, a horizontal line will be observed.

Suppose it is desired to observe a sinusoidal voltage waveform on the oscilloscope face. This can be accomplished in the following manner. First we place S in position A so that a time base is provided. Next the sinusoidal signal to be observed is applied to the vertical amplifier. By doing so the electron beam will be deflected both horizontall and vertically. With these two waveforms applied simultaneously, graphical methods can be used to obtain the waveform appearing on the screen. This procedure is illustrated in Figure 4.


Resulting
Waveform
on
C.R.T.
V
T
0
1
2
3
4
Voltage applied to
Vertical Amplifier
(Waveform to be
observed)
V
Voltage applied to Horizontal
Amplifier (provides time base)
Time

Graphical method of determining resulting waveform
Figure 4

The two amplifiers are required since in many cases, the voltage levels of some signals to be observed are so small that the electron beam will not be deflected sufficiently. The amplifiers will amplify the signal to such a value that the electron beam can be deflected enough to be observed. In order to obtain correct data from the waveforms observed on the screen, it is essential that the gains of both amplifiers be properly calibrated. The procedured is usually given in the instruction manual that comes with the oscilloscope.

The power supply provides the d - c voltages which the circuits and the CRT require. In a - c analysis, it is sometimes required to determine the phase angle between two signals. This can be accomplished by switching the position of the switch to position B. In doing so the time base generator is bypassed. We are now allowed to apply a signal to the horizontal amplifier. Applying two a - c signals of the same frequency but of different phase angles results in a pattern of the scope face. This is known as a Lissajous' figure. From this pattern, we can determine the phase angle between the two signals. This is one of the many measurements which can be made with the aid of an oscilloscope.

Laboratory Operation Procedure:

1. Obtain a Fairchild 701 Instructional manual and become familiar with the oscilloscope and its controls. Make a list of each control and its function.
   Note that the control that is marked TIME/CM and VOLT/CM is the switch that was discussed earlier. When this control is in the TIME/CM position, the switch is in position A. As can be seen, there are several frequencies to be selected from. When this control is on the VOLT/CM position, the time base generator is bypassed (switch in position B). There are two or three different gains which can be selected in this position.
2. Calibrate and balance the horizontal and vertical amplifiers.
3. Set up the oscilloscope so that two separate d - c potentials may be applied directly to the vertical and horizontal plates. Center the spot on the screen. Apply a d - c potential to the vertical plates and record voltage and deflection (CM). Plot voltage versus deflection. This should plot into a straight line since the deflection

sensitivity (volts/cm) is essentially a constant. Reverse the polarity and repeat the above procedure.

4. Repeat step 3 for the horizontal plates.
5. Calculate the deflection sensitivity for the horizontal and vertical plates.
6. Apply an equal voltage to both plates. Increase in steps this voltage and observe the path followed by the spot.

Phase 1

Preparation Test:

1. Name the three parts of the cathode - ray - tube and their function.
2. Draw a block diagram of the basic oscilloscope.
3. What is the function of a time base generator?
4. Why must the amplifiers be calibrated?

Phase 1

Concluding Discussion:

This problem has served the purpose of introducing the oscilloscope. In following problems much use of the oscilloscope will be made. For example, in a - c work it will be used to make phase and frequency measurements. The oscilloscope will also be used to obtain vacuum tube and transistor characteristic curves. For the present it is sufficient that the student understand the function of each knob on the oscilloscope face.

PRINCIPAL PROBLEM

NUMBER 3

R C TRANSIENTS

Statement of the Problem:

Many electronic systems such as radar, television, and computers require circuits which change the form of an incoming signal to some desired shape. A circuit which performs such a function is usually called a waveshaping circuit. Many of these circuits utilize RC, (resistive - capacitive), networks and RL, (resistive - inductive) networks. The purpose of this problem is to introduce some of the basic principles of RC networks.

Phase 1 Transient Analysis of RC Networks

Facts and Principles to be learned in this problem.

1. Capacitor charging and discharging through a resistor.
2. Voltage across a capacitor cannot change instantaneously.
3. Characteristics of simple RC waveshaping circuits.

Preliminary Discussion:

One of the basic definitions of capacitance is; $C = \frac{Q}{V}$

The above expression states that the capacitance of a capacitor is equal to the ratio of the charge on the capacitor to the voltage across the capacitor. When analyzing RC networks, we must keep in mind that the charge on a capacitor and therefore the voltage across a capacitor cannot change instantaneously. This is a fundamental but very important point to keep in mind. Most RC circuits can be reduced by Thevenin's Theorem to a simple series circuit consisting of a d - c source, a resistor and a capacitor. Let us consider the circuit shown in Figure 1.

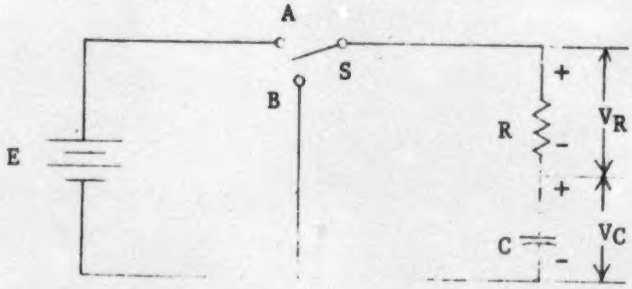


Figure 1 - Series RC Circuit

At t = 0 switch S will be placed in position A. At t = 0, we will assume that there is no charge on the capacitor and therefore no voltage across the capacitor. After a sufficiently long time, the capacitor will charge to the battery voltage E, and current will cease to flow.

Initially the voltage across the capacitor is zero and its final voltage is E. It can be determined by mathematical analysis, that the voltage waveform varies exponentially in the time that the capacitor is charging to the battery voltage. Let us look into this matter a little closer. At t = 0 the switch is closed and the applied voltage is E. Now since the capacitor voltage cannot change instantly from zero, the voltage across the resistor has to jump instantly to E volts in order for Kirchoff's voltage law to hold. This is seen by writing Kirchoff's law

$$E = V_R + V_C$$

and initially (t = 0), $V_C = 0$

Therefore

$$V_R = E$$

Now since $V_R = i_R$,

$$i_R = E$$

solving for i,

$$i = \frac{E}{R}$$

we see that at t = 0, the current jumps instantly to E/R amps. This initial current flow soon places a small charge on the capacitor. Since $V = \frac{Q}{C}$ a small voltage will appear across the capacitor. This small voltage is in opposition to the battery voltage, therefore the current must decrease and the capacitor will charge more slowly. This process continues until the capacitor becomes fully charged and the voltage across it equals the battery voltage. At this time the voltage across the resistor is zero since no current flows in the circuit. The diagrams below illustrate the manner in which the current, the voltage across the resistor and the voltage across the capacitor vary with time.

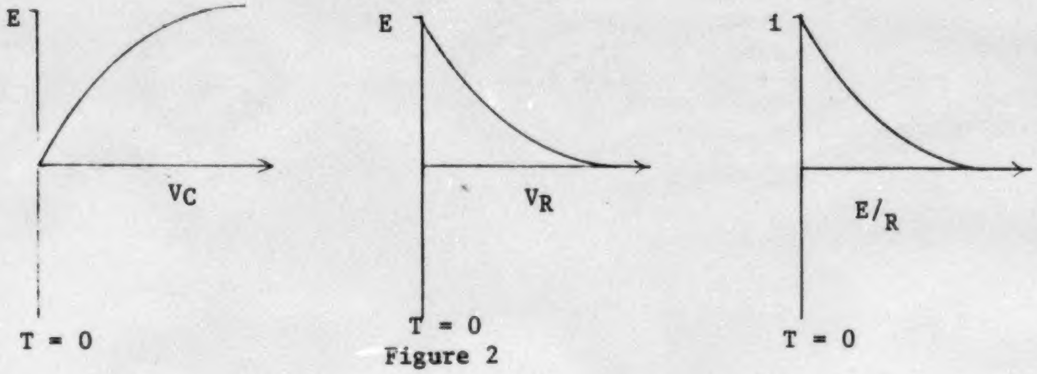


Figure 2

Note that at every instant that Kirchoffs' voltage law must hold. Therefore at every instant the voltage drop across the resistor plus the voltage drop across the capacitor have to equal the battery voltage E.

The capacitor charges to the battery voltage E and the time it takes to get there depends on the resistor and capacitor sizes. We will now introduce the concept of a time constant (τ). For a simple series RC circuit, the time constant is equal to the product of R and C.

One time constant is equal to the time required to charge a capacitor to 63 per cent of its final voltage or for a capacitor to discharge to 37 per cent of its final voltage. In general we can assume that the charging or discharging, whichever is the case, is completed after five time constants, (5τ).

Now suppose that the switch has been held in position A, a sufficient time ($t > 5\tau$) so that the capacitor has been charged to the battery voltage

E. At $t = t_1$ the switch is placed in position B thus placing a direct short across the charged RC network. Since the voltage across the capacitor cannot change instantly, then any sudden change in voltage must appear across the resistor. Writing Kirchoff's voltage law at $t = t1$ yields

$$0 = V_R + V_C = V_R + E$$

Therefore

$$V_R = -E.$$

Thus we see that the voltage drop across the resistor must suddenly drop to -E volts. This means therefore that since $V_R = i_R$, that the current must instantaneously drop to -E/R. The capacitor voltage will then start to decay exponentially to zero as will the voltage drop across the resistor, V_R, and the current i. This is illustrated in Figure 3. Note that the time constant for this circuit is also equal to, $\tau = RC$. Therefore these exponentials decay to zero at the same rate as when the capacitor was charging.

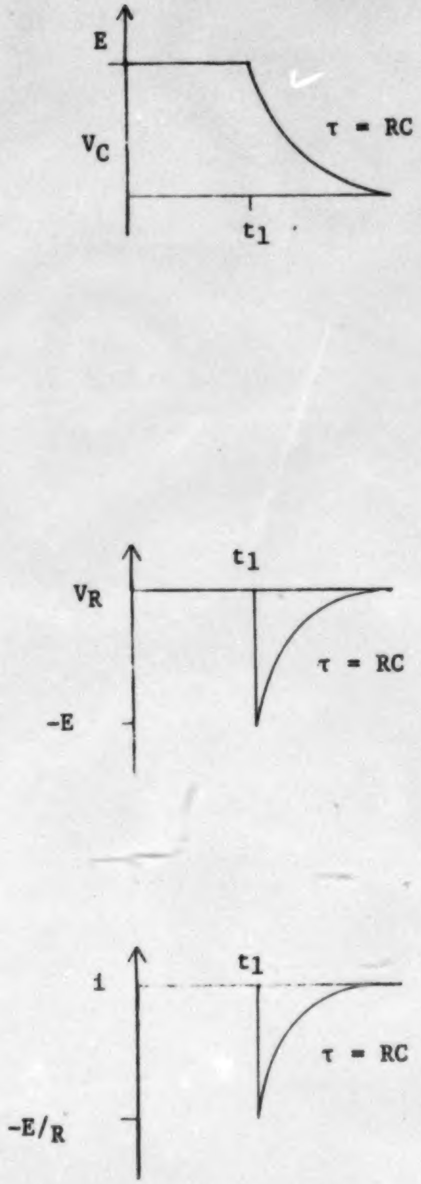


Figure 3

We will now give without proof, the equations for the buildup of a voltage across a capacitor with zero initial charge;

$$V_C = E\,(1 - e^{-t/RC}) \qquad (1)$$

where V_C is the capacitor voltage at any time t. The voltage decay across the resistor is given by,

$$V_R = E\ e^{-t/RC} \qquad (2)$$

where V_R is the voltage drop across the resistor at any time t.

Thus, for a given RC network, we can determine V_R and V_C at a given time by substituting into equations 1 and 2.

Instead of substituting into equations (1) and (2), we can develop two universal curves which can be used for any circuit. Dealing with equation (1), we first normalize the equation by dividing both sides by E.

$$\frac{V_C}{E} = 1 - e^{-t/RC} \qquad (1A)$$

now letting $x = \frac{t}{RC}$, we can write the above expression as

$$\frac{V_C}{E} = 1 - e^{-x} \qquad (1B)$$

Similarly dealing with equation (2),

$$\frac{V_R}{E} = e^{-x} \qquad (2A)$$

From math tables we can plot equations (1B) and (2A) for different values of x. These two plots result in universal exponential curves, shown in Figure 4. Note that these curves can also be used to determine exponentially decaying or rising currents also.

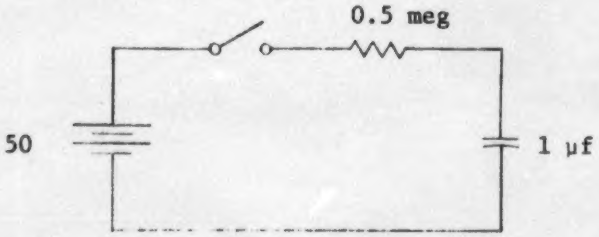
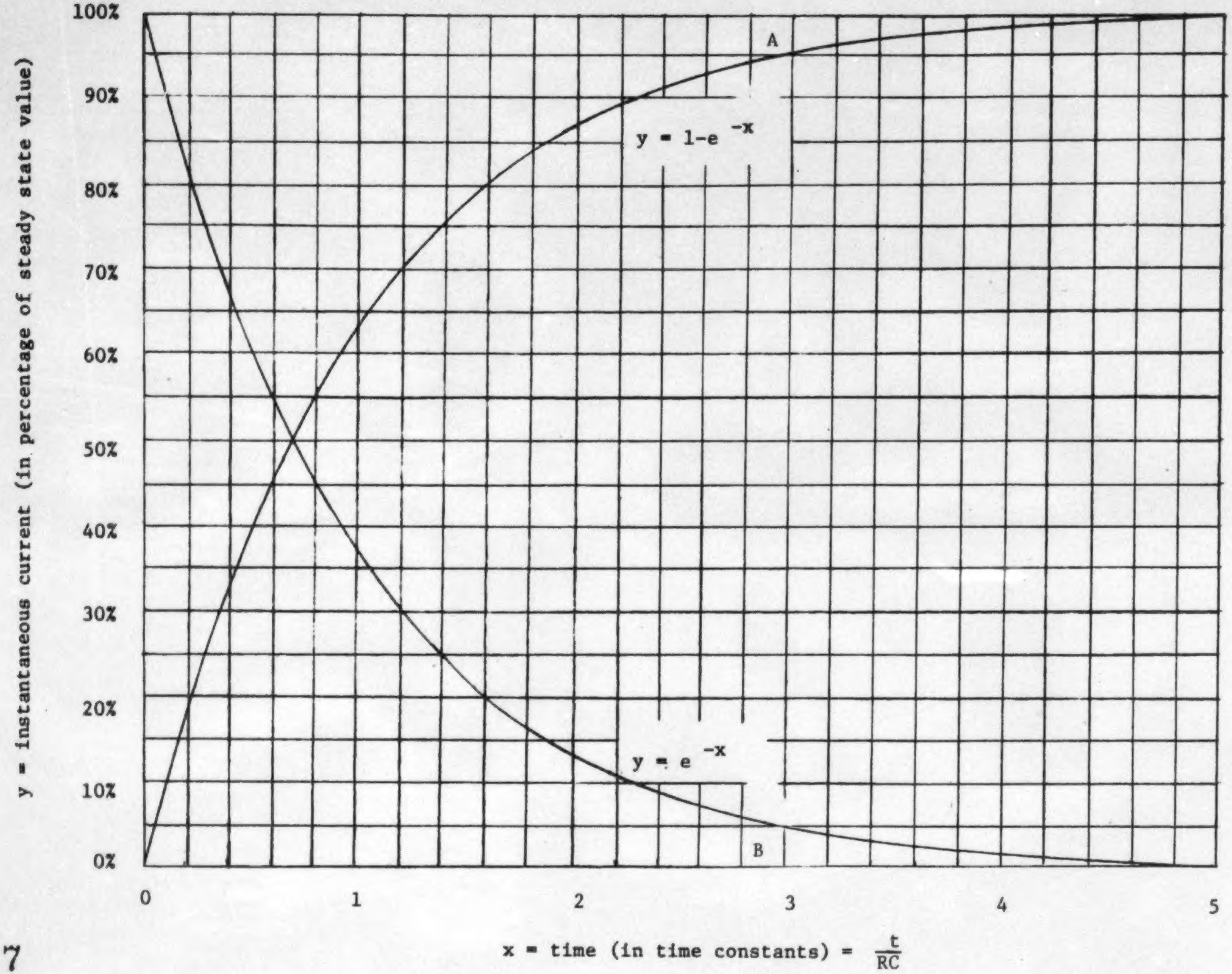


Figure 5 - Simple RC Circuit

As an example, let us consider the simple RC of Figure 5. Assume $V_C = 0$ initially. Suppose it is desired to determine the voltage across the resistor and capacitor 1 sec. after the switch is closed.


y = instantaneous current (in percentage of steady state value)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
A
$y = 1-e^{-x}$
$y = e^{-x}$
B
0
1
2
3
4
5
x = time (in time constants) = $\frac{t}{RC}$

First we know that the capacitor voltage will start from zero and rise exponentially to 50v. The resistor voltage will start at +50 v and decay exponentially to zero volts.

Solving for x,

$$x = \frac{t}{RC} = \frac{1 \text{ sec}}{(.5 \times 10^6)(1 \times 10^{-6})} = \frac{1}{.5} = 2$$

From curve A, we find that at x = 2 the capacitor voltage has risen to 86% of its final value.

Therefore at x = 0.5 sec.,

$$V_C = .86\ (50) = 43 \text{ volts.}$$

From curve B, the resistor voltage is down to 14% of its maximum value or,

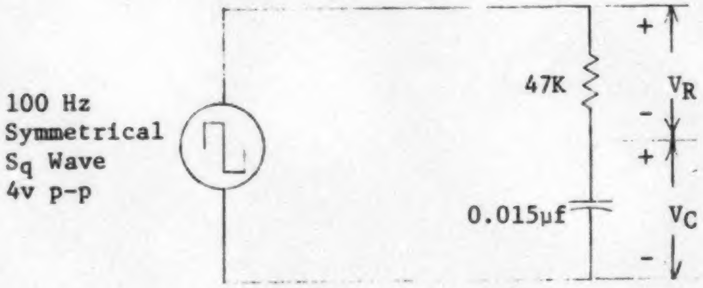
$$V_R = .14\ (50) = 7 \text{ volts.}$$

Note that at this instant that Kirchoff's voltage law holds.

$$V_C + V_R = 50$$

Laboratory Operation Procedure:

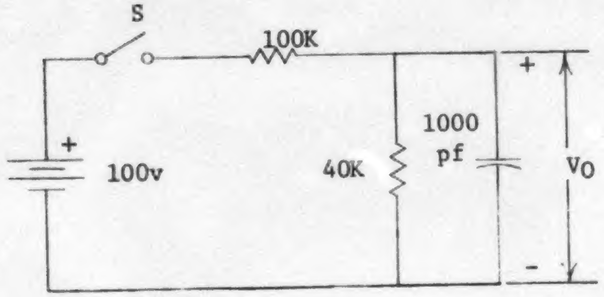
1. Connect the circuit shown in the figure below.



2. Obtain and sketch V_R and V_C.
3. Determine the time constant from the exponential rise and decay.
4. Compare this with the value obtained by multiplying R and C.

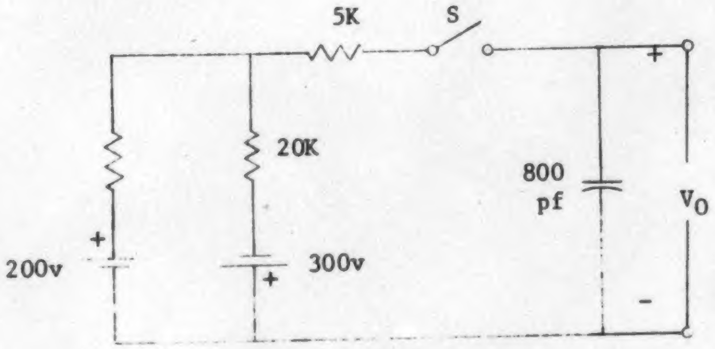
Preparation Test:

1. For the circuit shown, determine V_O 75 μsec after the switch is closed.


S
100K
+
100v
40K
1000
pf
+
V_O
-

Problem No. 1.

2. For the circuit below, determine the capacitor voltage 20 μsec. after the switch has been closed.

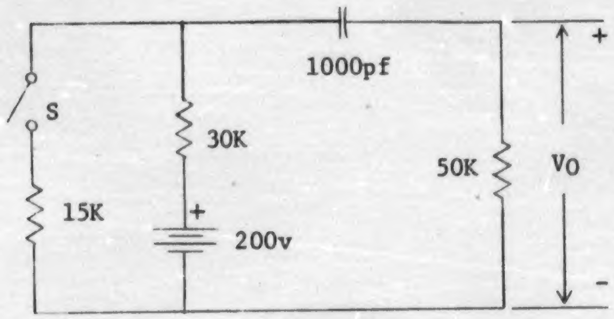

5K
S
+
20K
800
pf
V_O
+
200v
300v
+
-

Problem No. 2.

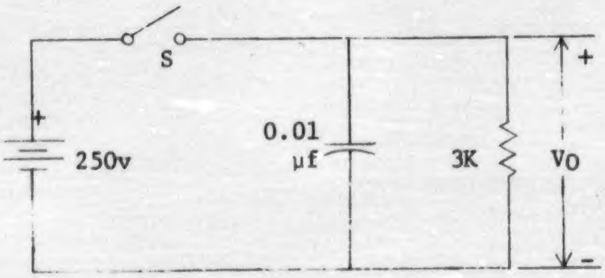
Homework Exercise:

1. By graphical and analytical methods, determine the voltage, V_O, for each of the following circuits, at 100 μsec. after S is closed.

(A)


1000pf
S
30K
15K
+
200v
50K
V_O
+
-

(B)


S
+
250v
0.01 μf
3K
V_O
+
-

151

Concluding Discussion:

Since resistors and capacitors can be manufactured to precise tolerances it is possible to make precision timing networks from the combination of a resistor and capacitor. The precision of the time interval is often not limited by the resistor or capacitor but by the precision of the network which reads the timing voltage. We shall see later that the time constant is the natural frequency of the circuit. If the capacitor is charged to a test voltage level, then connected to a resistance network, the capacitor will discharge at some natural frequency. If the resistance - capacitance network is part of a voltage amplifier, the reciprocal of the time constant may determine the frequency above which the voltage gain is below 0.707 times the mid frequency gain. In short the time you spend in understanding time constants is a necessary step toward understanding the frequency dependence of many types of circuits.